**ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY**

# DEVELOPMENT OF TRAILER TRUCK ENGINE DUTY CYCLE FOR TURKEY USAGE PROFILE

**M.Sc. THESIS**

**Fatih ÜNAL**

**Department of Mechanical Engineering**

**Automotive Programme**

**MAY 2014**

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**Thesis Advisor: Prof. Dr. Cem SORUŞBAY**

**MAY 2014**

**İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ**

# ÇEKİCİ ARAÇ MOTORLARI İÇİN TÜRKİYE KULLANIM KOŞULLARINI TEMSİL EDEN SEYİR ÇEVRİMİ OLUŞTURULMASI

**YÜKSEK LİSANS TEZİ**

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**Otomotiv Programı**

**Tez Danışmanı: Prof. Dr. Cem SORUŞBAY**

**MAYIS 2014**

**Fatih ÜNAL**, a M.Sc. student of ITU Graduate School of Science Engineering and Technology student ID 503101728, successfully defended the thesis entitled "**Development of Trailer Truck Engine Duty Cycle For Turkey Usage Profile**", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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**Date of Submission : 22 April 2014**
**Date of Defense : 27 May 2014**

***To my family,***

# FOREWORD

I'm grateful to my advisor, Prof. Dr. Cem Soruşbay, for his practical advice and encouragement. I am also thankful to the people which have contributed and made this thesis possible. Most importantly, this study would not be possible without help, the patience and love of my family.

May 2014

Fatih ÜNAL
(Mechanical Engineer)

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## ABBREVIATIONS

| | |
|---|---|
| **WHTC** | **:** World Harmonized Transient Cycle |
| **UNECE** | **:** United Nations Economic Commission for Europe |
| **ECE** | **:** Economic Commission for Europe |
| **ESC** | **:** European Stationary Cycle |
| **ELR** | **:** European Load Response |
| **ETC** | **:** European Transient Cycle |
| **GTM** | **:** Gross Trailer Mass |
| **GPS** | **:** Global Positioning System |
| **WHDC** | **:** Worldwide Harmonized Driving Cycle |
| **ABS** | **:** Anti-lock Braking System |
| **GVM** | **:** Gross Vehicle Mass |
| **IP** | **:** Ingress Protection |
| **OBD** | **:** On-board Diagnostics |
| **OEM** | **:** Original Equipment Manufacturer |
| **GPRS** | **:** General Packet Radio Service |

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**DEVELOPMENT OF TRAILER TRUCK ENGINE DUTY CYCLE FOR TURKEY USAGE PROFILE**

## SUMMARY

Today at the heavy-duty engine development studies, to achieve reliable and low cost products are the key elements. To meet both challenging targets, tailor based engine design and engine validation studies for major markets are applied in the industry. Conducting tailor based design and validation requires the real world usage information of the engine to be developed for the targeted market. There is an increasing demand in the industry to understand the Turkey trailer truck duty cycle to support technology evaluation efforts, create customer correlated engine test procedures and calculate lifetime of the engine components to support engine design studies.

The conventional method to develop engine duty cycle is to collect data from real world users in the field with serial production vehicles. In product development studies, especially in brand new designs, the conventional method is not effective. For the engines in the design or validation phase, to collect data from the real world users is not applicable, because in the field, it is not possible to find a vehicle equipped with the prototype engine which is under development. The approach is to collect the closest power rating engine data and develop engine duty cycle. This method reduces the accuracy of the results and the representativeness of the duty cycle. At new technology development studies, collecting closest power-to-weight ratio engine data does not give result because the engine is not equipped with the component which is a new technological application.

In this study, discrete drive duty cycle methodology is used. This methodology predicts the engine duty cycle collecting data from a vehicle with prototype engine that run at the public routes with pre-determined routes and driving types with various professional drivers. The type of driving behaviors and routes are determined conducting driver questionnaire and using the public road heavy-duty usage statistics. Engine duty cycles are developed for 10.3L 420PS and 10.3L 460PS trailer truck vehicles for Turkey conditions combining the discrete drives collected from public routes and their weights that is obtained from driver survey and statistical operations. Duty cycles of both engines are compared in terms of engine speed and engine percentage load. Finally, developed engine duty cycles are compared with the Worldwide Reference Transient Engine Cycle.

**ÇEKİCİ ARAÇ MOTORLARI İÇİN TÜRKİYE KULLANIM KOŞULLARINI TEMSİL EDEN SEYİR ÇEVRİMİ OLUŞTURULMASI**

## ÖZET


Günümüzde, ağır ticari araç motorları geliştirme çalışmalarında, güvenilirliği yüksek ve maliyeti düşük motorlar geliştirmek üretici firmaların rekabet edebilmesi açısından önemli bir hedef konumuna ulaşmıştır. Ağır ticari araç üreticileri yüksek güvenilirlik ve düşük maliyet hedeflerini gerçekleştirebilmek için, motorların ana pazarlardaki kullanım koşullarını dikkate alarak, ilgili pazarlar için özel motor tasarım ve motor tasarım doğrulama çalışmaları gerçekleştirmektedir. Bu kapsamda hedef pazarlar için kullanım koşulu verilerinin toplanması ve verilerin yüksek doğrulukta analiz edilerek seyir çevrimleri oluşturulması yüksek bir önem kazanmıştır.

Genişleyen Türkiye ağır ticari çekici sınıfı araç pazarı, ağır ticari araç üreticilerinin çekici araç motorları için Türkiye kullanım koşullarını temsil eden seyir çevrimi ihtiyacını ön plana çıkarmaktadır. Motor seyir çevrimi, motor hızı ve motor yüzde yükünün temsili sürüş için yüzde dağılımını veren üç boyutlu bir histogramdan oluşmaktadır. Motor seyir çevrimlerine, motor teknoloji geliştirme çalışmaları, hedef pazar kullanım koşullarını temsil eden motor test prosedürlerinin oluşturulması, motor tasarım fazı esnasında, motor sistem ve alt sistemlerine ait parçaların ömür hesaplarının yapılması ve kalibrasyon geliştirme alanlarında ihtiyaç duyulmaktadır.

Motor geliştirme aşamalarında, seyir çevrimlerinin vereceği bilgiler ışığında motor parçalarının malzeme ve geometri değerleri değiştirilmekte ve en iyileme işlemi gerçekleşmektedir. Motor tasarım çalışmalarına ek olarak, motor test geliştirme çalışmalarını da seyir çevrimleri beslemektedir. Prototip aşamada olan bir motorun tasarım doğrulama test planı oluşturulma safhasında, saha kullanımı dikkate alınarak korelasyon çalışmaları gerçekleştirilmekte, test süreleri ve çevrimleri belirlenmektedir. Tasarım ve tasarım doğrulama çalışmalarına ek olarak, motor seyir çevrimleri motor kalibrasyon çalışmalarının en iyileme işlemlerini gerçekleştirmek için kullanılmaktadır. Kalibrasyon en iyileme işlemlerinde, motor çevrimlerinde yoğun olarak kullanılan bölgeler baz alınmakta ve çalışmalar bu bölgelerde odaklanmaktadır.

Konvansiyonel motor seyir çevrimi geliştirme yöntemlerinden biri, sahada bulunan, seri üretimi gerçekleşmiş araçlara, veri kaydedici cihazlar yerleştirilerek kullanım profillerinin kaydedilmesidir. Bu yöntemde gerçek araç sürücüleri veya profesyonel araç sürücüleri kullanılmaktadır. Veri cihazları yerleştirilmiş araçlar günlük rutinlerini gerçekleştirdikleri sırada, motor seyir çevrimi için gereken verilerin kaydedilme işlemi yapılmaktadır. Araçlar üzerinde direk kontrol imkanı olmadığından, düzenli olarak veri aktarımı yapmak bu yöntemde mümkün olmamaktadır. Bu sebeple araçlara yerleştirilen veri kaydetme cihazları gerçek zamanlı verileri kaydetmek yerine veri gruplama işlemini gerçekleştirmedir. Veri gruplama işlemi kaydedilen kanallardaki değerlerin sıra bilgilerini içermemektedir.

Motor parametrelerinin belirli değerlere kaç defa ulaştığının sayımı bu süreçte mümkün olamamaktadır. Bu bilgi parça yorulma hesaplarında önemli bir yer teşkil etmektedir. Veri kaydetme cihazlarına periyodik olarak erişim imkanı olmadığından, cihazda sorun meydana gelmesi halinde veri kayıpları oluşmakta ve çalışma sonucunda veri elde edilmeyebilmektedir.

Yöntemin diğer bir dezavantajı ise prototip motorlar kullanılarak seyir çevrim çalışması yapılamamasıdır. Motor seyir çevrimi doğruluğunun arttırılması için seri üretimde mevcut olan en yakın güç-ağırlık oranına sahip araçlar kullanılmakta ve çalışmalar bu araç ile yürültülmektedir. Yeni teknolojilerin uygulandığı motorlarda, seri üretimde bulunan motorlar ile seyir çevrim çalışması yapmak, sonucun temsil etmedeki başarısını ve doğruluğunu dramatik olarak azaltmaktadır. Sahada bulunan araçlar üzerinden veri toplama işleminin avantajı ise öngörülemeyen kullanım koşullarını tespit etmek, iklim ve çevre koşullarını seyir çevrimine dahil etmek ve farklı sürücülerden kaynaklanan varyasonların etkisini de seyir çevrimi içerisine katmaktır.

Prototip safhadaki motorlarda seyir çevrimi bilgisi oluşturmak için konvensiyonel yöntemler etkili sonuçlar vermemektedir. Bu çalışmada ayrık sürüş yöntemi kullanılarak 10.3L 420 PS ve 10.3L 460 PS motorlara sahip 40 ton yüklü çekici araçlar için Türkiye kullanım koşullarında motor seyir çevrimi belirleme çalışması yapılmıştır. Ayrık sürüş yöntemi, kullanıcıların temsili sürüş tiplerini ve yol tiplerini istatiktiksel yöntemler kullanarak belirlemek ve belirlenen yol ve sürüş tiplerinde profesyonel bir sürücü ile saha kullanımını temsil edecek şekilde aracı kullanmayı kapsamaktadır. Ayrık sürüşler gerçekleştirilip, belirlenen motor parametrelerinin kaydı tamamlandıktan sonra, ilgili sürüşler istatiksel yöntemler kullanılarak ağırlıklandırılmakta ve Türkiye koşullarını temsil eden seyir çevrimi oluşturulmaktadır.

Seyir çevrim çalışması Türkiye koşulları için kullanım istatistiklerinin oluşturulması ile başlamıştır. Türkiye’nin çeşitli illerinde bulunan 486 çekici sınıfı ağır ticari araç kullanıcısına hangi yol çeşitlerinde, hangi kullanım çeşitlerinde, hangi sıklıkla araçlarını kullandıklarına dair sorular sorulmuştur. İstatiktiksel çalışmanın doğruluğu, seyir çevriminin kullanım koşullarını temsil etme oranını yüksek şekilde etkilemektedir. Kullanıcı istatistiğinin doğruluğunu arttırmak amacıyla anketler yüksek maliyetli ve zaman alan bir metod olan yüz-yüze anket metodu kullanılarak gerçekleştirilmiştir. Yapılan yüz-yüze anketler sonucunda, yol tipleri, sürüş tipleri ve ağırlıkları oluşturulmuş ve sınıflandırma matrisi olarak adlandırılmıştır. İstatistiksel sonuçlara bakıldığında çekici tipi araçlar için Türkiye koşullarında; şehirler arası otoyol, şehirler arası bölünmüş devlet yolu ve köy yolu olarak üç farklı sınıflandırma yapılmıştır. Kullanım çeşidi olarak ise agresif, ortalama kullanım ve hafif kullanım belirlenmiştir. Gerçekleştirilen anketler sonucunda yol tipleri ve sürüş tipleri için her bir sürücünün yüzde sürüş oranı elde edilmiştir. Anketlerin doğruluğunu arttırmak amacıyla çapraz sorular eklenerek sonuçlar kontrol edilmiştir. Cevapların doğruluğunu arttırmak amacıyla sorular sürücülere yazılı olarak dağıtılmasına rağmen sözlü olarak da her bir soru hakkında açıklamalar yapılmıştır.

Yol ve sürüş tiplerinin toplam sürüşe olan ağırlıklarının belirlenmesinden sonra yol tiplerini temsil edecek rotaların bulunması aşamasına geçilmiştir. Bu aşamada karayollarının ağır ticari araçlar yoğunluk haritası ve anket sonuçları kullanılmış, ayrıca deneyimli ağır ticari araç kullanılcılarından da bilgiler alınmıştır. Rota belirleme çalışmaları için sürücü konaklama kısıtı bulunmaktadır. Aracın her 16 saatte bir test kontrol noktası olan Gölcük Kocaeli'ye uğrayarak sürücü değişimi yapılması gerekmektedir. Bu sebeple rota belirleme çalışma Marmara bölgesinde gerçekleştirilmiştir. Karayolları yoğunluk haritası incelendiğinde Türkiye ağır ticari araç yoğunluğunun büyük bir bölümünün Marmara bölgesinde olduğu gözlemlenmektedir.

Yol ve sürüş tipleri, rotalar ve herbirinin toplam sürüşteki ağırlığı belirlendikten sonra iki farklı araç ile yollarda veri toplamayı içeren ilk faz çalışması başlatılmıştır. İlk aşamada sürücülere yol tipleri, sürüş tipleri ve rotalar hakkında eğitimler verilerek deneme sürüşleri gerçekleştirilmiştir. Araçlar haftanın yedi günü, günde yirmidört saat koşacak şekilde sürüş planı hazırlanmıştır. Sürücüden sürücüye varyasonu da sonuçlara dahil etmek amacıyla, sürücüler sürüşlere dağıtılmıştır.

Veri toplama çalışması için 256 MB hafızaya sahip araç CAN hattından veri kaydetme özelliğinde, tek başına (bilgisayar gereksinimi olmaksızın) çalışabilen veri kaydetme cihazı kullanılmıştır. Veri kaydetme cihazına, zaman bazlı kayıt yapması için motor ve araçla ilgili 14 kanal tanıtılmıştır. Sıcaklık kanalları haricinde diğer kanallardan 10 Hz ile kayıt alınmıştır. Motor veya araç üzerine ek olarak herhangi bir enstrümantasyon yapılmamıştır, kaydedilen tüm değerler motor sensörlerinin ölçtüğü veya motorun hesaplayıp CAN hattına dağıttığı verilerden oluşmaktadır.

Kaydedilen veriler günlük bazda incelenerek, verilen sağlığı ve doğruluğu kontrol edilmiş ve veri kayıpları en aza indirgenmiştir. Veri analizi ve kontrolü için MATLAB programı kullanılarak veri analiz kodları oluşturulmuştur. Veri sağlığı ve veri düzeltme yöntemleri veri analiz kodları yoluyla gerçekleştirilmiştir. Kodlar herhangi bir olumsuzluğu kullanıcıya bildirmiş ve ilgili düzeltme kullanıcının insiyatifine bırakılmıştır. Veri düzeltmede insan kontrolüne dayanmayan otomatik yaklaşım hataya mahal verebileceğinden tercih edilmemiştir. 10.3L 420 PS ve 10.3L 460 PS araçlardan toplamda 18 GB veri elde edilmiş, tüm veriler MATLAB programı ile yapılandırılarak analiz edilmiştir.

Veri toplama ve analiz süreçlerinin ardından dokuz farklı kullanım şeklinin motor hızı ve motor yüzde yük kullanım haritaları oluşturulmuştur. Motor seyir çevrimi oluşturmak için sınıflandırma matrisinde bulunan ağırlıklar ve her bir sürüş tipinin haritası kullanılarak iki farklı çekici tipi araç için Türkiye kullanım koşullarını temsil edecek motor seyir çevrimleri oluşturulmuştur. Motor seyir çevriminde kullanılan haritalardan aynı sürüş için birden fazla olması durumunda ortalamaları alınmıştır.

Çalışma sonucunda elde edilen seyir çevrimleri incelendiğinde, düşük yük bölgesinin çekici sınıfı araçlar için önemli bir kullanım alanı teşkil ettiği sonucuna varılmıştır. Düşük yükte çalışma oranı 29.6 % ile 35 % arasında değiştiği gözlemlenmiştir. Ek olarak motorun rölantide geçen zamanın 6.42 % ile 7.74 % arasında olduğu tespit edilmiştir. Motor yüzde yükünün 95 % ile 100 % arasında bir tepe yaptığı her iki araçta da görülmüştür.

Türkiye koşullarını temsil eden motor seyir çevrimini WHTC ile karşılaştırmak amacıyla 10.3L 420 PS aracın WHTC çevrimi oluşturulmuştur. 10.3L aracın Türkiye kullanım çevrimi ile WHTC çevrimi arasındaki kullanımda büyük farklılıklar gözlemlenmiştir. WTHC çevriminin düşük hızlarda ve düşük yüklerde daha fazla zaman geçirdiği sonucuna varılmıştır. Türkiye çekici tipi araç motor seyir çevrimleri için WHTC'nin yakınsama değerinin düşük olduğu tespit edilmiştir. Emisyon regülasyonları dışında, motor ve motor tasarım doğrulama çalışmalarında ayrık seyir çevrimi geliştirme yöntemi ile oluşturulan seyir çevriminin kullanılmasının sonuç doğruluğunu arttıracağı belirlenmiştir.

# 1. INTRODUCTION

Today in the heavy duty engine design; developing robust, durable and low cost engines are critical for the manufacturers to deliver successful projects. To achieve this goal tailor made design, testing and calibration studies are required for the targeted markets. Tailor made studies targets to change design and testing requirements from market to market analyzing the targeted population engine usage characteristic. The engine duty cycle can change significantly between the vehicle usages on different areas of the world. To conduct tailor made studies, a clear definition of engine operating conditions in each targeted market should be defined. Without defining the usage at the field, the studies can be resulted with over and under design, which are directly correlated with the cost and the quality of the product. In addition, the optimization efforts of the engine calibration should be conducted using the points where the field usage is intense. With this strategy, the decrease in fuel consumption and increase in performance of the engine can be achieved.

Another part in engine development, which is affected by the real world usage profile, is the engine testing studies. In conventional approaches, the engines are subjected to thousands of testing hours, which are not analytically correlated with the field. The conventional tests are generally in the form of pass and fail tests. The lack of the correlation may lead components or systems to be over or under designed. If any failure occurs during the engine testing, the correlation of the test hour with the field usage cannot be made so that to feedback to improve design is limited in the conventional test approaches. However, with using the clear definition of the market engine usage profile, the duty cycle, analytical tests which are correlated with the field, can be created. Using the damage model based test acceleration methods the time of the tests can also be shortened, so that the results can be gained in much shorter times in engine design validation phases which are getting shorter with high market demand.

With the field correlated design and validation approach; the design, quality and reliability issues of the product can be detected at the earlier phases of the product life cycle. At Figure 1.1, the graph of the “Rule of Ten” can be found. To decrease the costs per failure, it is necessary to take actions at the earlier phases of design rather than at the later parts. To take actions, failures should be detected at the design validation phase which can effectively done using the analytical test approach that has the field correlation. Otherwise, the costs can dramatically increase if the reactions are not given at early period. It can be observed that the tailor based engine development is combined with the failure prevention and failure detection strategies on the design phases.

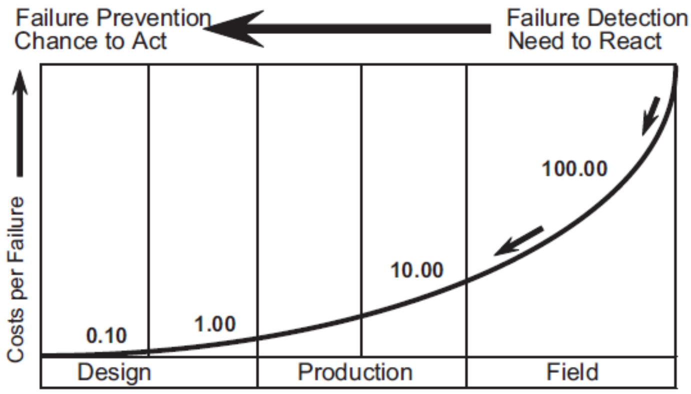


**Figure 1.1 :** Cost per failure versus product life [1].

To develop engine duty cycle for targeted markets, conventional method is to collect data from the real world drivers which use the serial production vehicles. This method requires high number of data loggers and long period of logging time in the field. Increasing the number of samples from the field, the duty cycle of the market can be calculated in an accurate manner. However, with this type of method, it is not possible to take time based data on many applications because of the long recording times that exceeds the data logger memory capacity, for that purpose data binning method is used. The data binning method has some disadvantages like losing the time based data which can be used for counting the thermal events so that calculating the fatigue damage on engine components.

For engines that are on the design and validation phase, it is not possible to collect data from the real world users, because in the field, there is no vehicle equipped with the prototype engine being developed. The typical approach is to collect the closest power rating engine duty cycle data and use in the product development studies. This method neglects the field usage differences between engine in development and engine that is already at the field which can cause the decrease in the accuracy of the data.

In this project, discrete drive duty cycle development methodology is used. This methodology is based on collecting driving statistics from the field, determining the driving behavior and route type according to statistical data and collecting data from field with a vehicle equipped with prototype engine on the discrete drives and driving behaviors. Finally, duty cycle is created combining the discrete drives with their weight on the duty cycle. This method is advantageous for prototype engine development studies when comparing with traditional approach because it is possible to develop duty cycle for engines being developed. In addition, this method allows measuring and recording the time based data because there is periodical data transfer opportunity with planning the shifts accordingly. With this method, it is also possible to record more number of channels from vehicle data bus.

## 1.1 Objective and Approach

In this study, the main objective is to create engine duty cycle for 10.3L 420PS and 10.3L 460PS trailer truck engine using the discrete drive duty cycle methodology at Turkey driving conditions. Special applications such as the construction, mixer or garbage truck are not included in the development study as these applications require a separate usage characteristic analysis.

Currently to optimize the engine design, calibration and testing studies the commonly used engine cycle is World Harmonized Transient Cycle that is developed by the UNECE Group of Experts on Pollution and Energy. WHTC is developed to become a uniform global basis for engine certification regarding engine emissions [2]. In UNECE study, the Turkey driving conditions for heavy duty engine usage is not included; the UNECE study covers wide applications of heavy duty vehicles rather than including only trailer trucks. WHTC includes light trucks, rigid trucks, trailer trucks and public transportation buses which are run at Europe, United States, Australia and Japan. Duty cycle which is developed using the Turkey driving and statistical data is required to conduct efficient engine product development studies because there is no representative data available for Turkey trailer truck engine usage conditions.

## 1.2 Literature Review

The engine duty cycle is a mapping of engine speed and engine percentage load over the percentage residency over time. Emission cycles that run on engine dynamometers are also referred as duty cycles, at these cycles, the emission values are measured and compared with various applications. This type of engine emission cycles are also based on the real world driving data from the field and represent the parts of the field usage. However, the emission cycles are created to develop emission standards, so that the duty cycle methodology at this cycles are based on considering the usage conditions which is important for emission measurements. This type of cycles can be continent based, international and some of the emission cycles can be local. However, for each targeted market, finding engine emission cycle to use in engine development studies may not be possible. So that to create engine duty cycles for specific usage conditions are required. Emission cycles are very effective for performance and emission comparison of engines in product development phase, but for field representative results accurate duty cycle is needed. Without an accurate definition of field usage, product development studies may be directed to over or under design which is not desired.

For European heavy duty engine usage conditions there are some emission cycles that are developed. These cycles are; ECE R49, ESC and ELR, ETC. ECE R49 is a steady state cycle consists of a sequence of 13 engine test modes. ESC is steady state cycle consists of 13 engine test modes which are characterized by its high load factors and high exhaust gas temperatures [3]. ELR consists of a sequence of three load steps with three engine speeds followed by a cycle of different speed and load.

ETC is a transient cycle that contains the three parts; urban, rural and motorway driving. Urban part represents city driving with frequent starts, idle and stops. Second part represents rural driving with high accelerations. The final part is motorway driving with high average speed [4]. ETC transient cycle engine speed and torque plots can be found at Figure 1.2 and Figure 1.3. World Harmonized Transient cycle is an international transient heavy-duty engine cycle. The cycle is specifically developed for truck and public road bus applications at Europe, United States of America, Australia and Japan. WHTC is widely accepted as a comparison basis of engine performance and emission measurements.

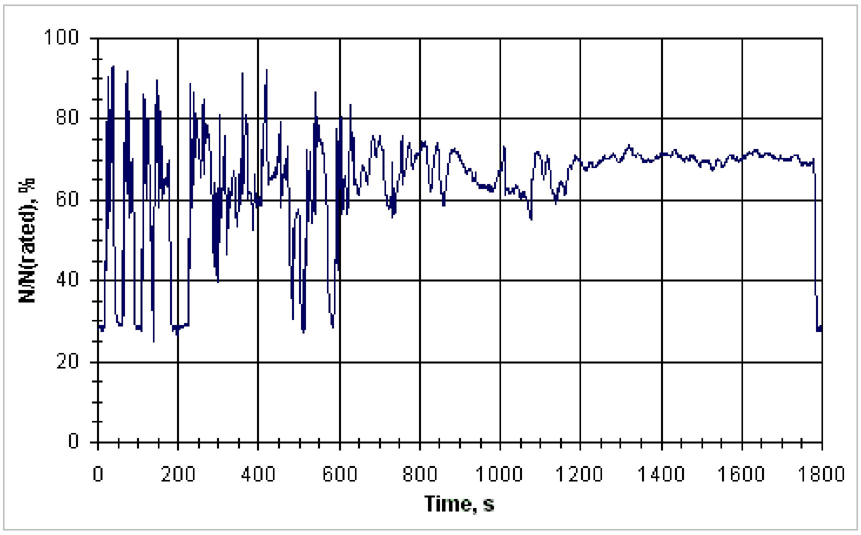


**Figure 1.2 :** ETC cycle engine speed [4].

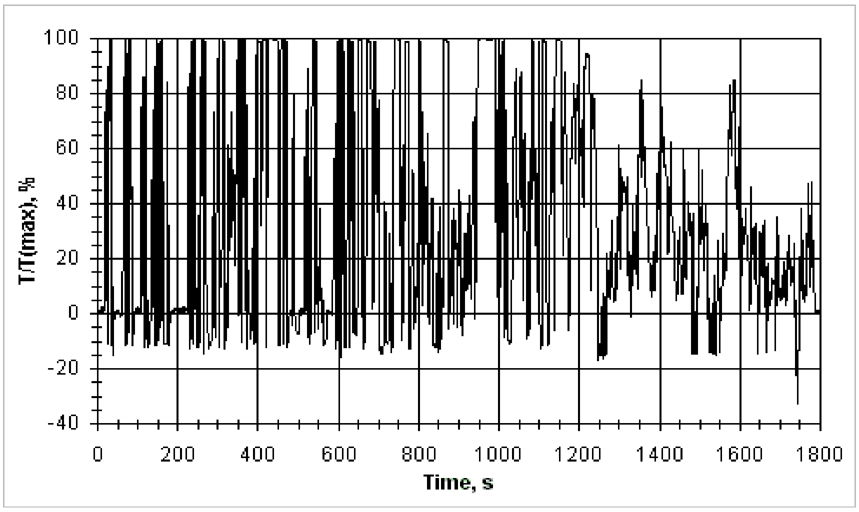


**Figure 1.3 :** ETC cycle engine torque [4].

The emission cycles are effective at emission measurement applications; however, these procedures are not covering all the points to use them for the engine product development activities because they intensively have the parts of the real world usage which is important for emission measurements.

In addition to emission duty cycles, there are efforts to develop heavy duty engine cycles to support technology evaluation efforts, create customer correlated engine testing procedures, calculate the lifetime of the engine components and comparison of real world driving performance of engine systems at the heavy duty truck operations. These kinds of studies are covering larger portions of the field data when compared to the emission cycle studies. There is an increasing trend in the industry to understand the heavy-duty truck field operation.

One of the recent large-scale heavy-duty truck duty cycle study is started at 2008 under the sponsorship of the Department of Energy's Office of Vehicle Technologies in the United States of America. In the study, from real world fleets, 700,000 miles of long haul data is collected which is more than 200 gigabytes to understand the usage profile of Class-8 heavy-duty truck application in the United States. Sixty channels of data at 5 Hz frequency is recorded from six instrumented tractors [5]. This study is an example of duty cycle methodology that is based on collecting real world data usage from the real world drivers at the field without any driving type classification and discretization.

Institute of Automotive Engineering of the Technische Universitat Braunschweig found a new approach called 3D method to classify the real world usage conditions into discrete events. The 3D method considers the driver behavior and characteristics of road while developing duty cycles [6]. There are three parameters in the method; driven vehicle, driving environments and driver. For driven vehicle; driver only, average, heavy and trailer options are listed. For driving environments; urban, extra urban, mountain and autobahn drivers are listed. Finally for driver; mild driver, average and sporty driver are listed. With four kinds of road, four kinds of load and three different drives, forty-eight possible driving combinations can be achieved. This method allowed splitting real world drives into the discrete events and collecting the usage percentages for each drive to construct duty cycle.

Duty cycles studies with discretization methods are used to create component accelerated key life tests. Renault lent several vehicles to customers at 2009 in order to record the specific channels related with engine. With this study, the company analyzed the characterization of the customer driving style and split the drive into; urban, road, highway or mountain use. The driving type of the vehicles are categorized as slow, rapid drive and soft, high acceleration. Distribution of the driving types is combined according to surveys and the engine duty cycle is created in terms of the engine speed and the engine torque for cylinder head reliability assessment and key life test development [7].

At 2010, discrete method is modified for heavy-duty applications. In cooperation with Daimler AG and the Institute of Automotive Engineering of the Technische Universitat Braunschweig, 3-D approach is established to analyze the component loads in real world usage condition [8]. The method is based on considering customer requirements on heavy-duty vehicles to cover reliability and durability with minimal cost weight of the vehicle. The 3D method systematically categorizes the driver operation, vehicle and driving environment and in this study it is applied to heavy-duty applications with some modifications on 3D parameters. The mild, average and sporty driving styles are changed with dynamic and economic. Driving environments; urban, extra urban, mountain and autobahn are changed with distribution, short distance transport, long distance transport and offroad [8]. Driven vehicle loads; trailer, full, average and light are changed with heavy, average and light which can be founded at Figure 1.4.

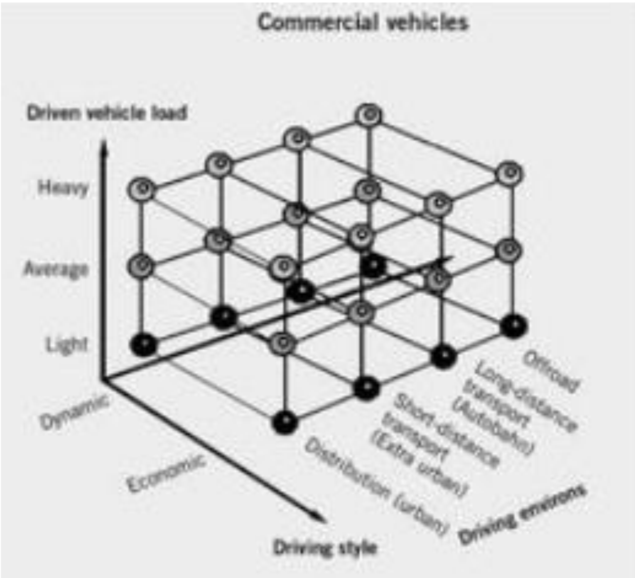


**Figure 1.4 :** 3D parameter spaces for commercial vehicle [8].

At 2010 Ford OTOSAN conducted a discrete drive based duty cycle study on heavy duty road truck vehicle which is called the Road Vehicle Data Collection Methodology. In this study duty cycle for a 9.0L 380PS road truck heavy duty vehicle is created for Turkey driving conditions. The methodology includes collecting usage statistics from the field by customer questionnaires and collecting real world data from a vehicle using the pre-determined discrete drives. 3-D method is also used in this study for discretization of the drives. Using the duty cycle data, 2400 hour system to system interaction test for heavy duty engine validation is created and this test is used instead of the conventional few operating mode engine durability tests [9]. At Figure 1.5 the customer correlated general durability transient engine test cycle for Ford OTOSAN 9.0L engine can be found. The correlated cycle also created time and cost benefit.

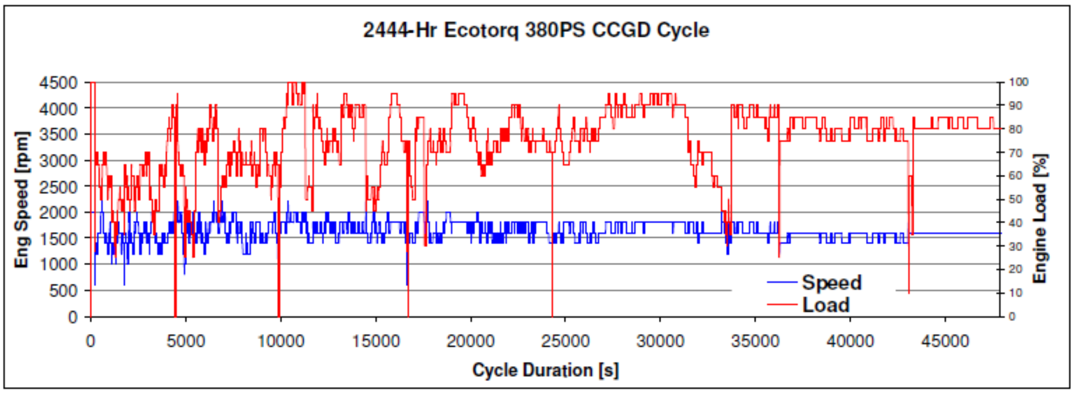


**Figure 1.5 :** Ford OTOSAN engine test cycle [9].

# 2. CLASSIFICATION OF EFFECTING PARAMETERS AND COLLECTION OF STATISTICS

In this study, data is collected from selected public routes with trailer trucks, using professional drivers to mimic the driver usage profile. This prediction methodology is sensitive for influential parameters affecting the heavy-duty trailer truck load collective. A proper definition of important parameters at the start of the study is essential to create a reliable and representative output; the engine duty cycle.

Engine duty cycle consists of two different parameters; engine speed and engine percentage load. The engine percentage load is defined as the engine torque at specified engine speed divided by maximum available torque at that engine speed. The main parameters affecting the engine torque and engine speed are; route type, vehicle type, road gradient, driving behavior and vehicle load. Route type, vehicle type and driving behavior are taken into account at this study. The road gradient is not included since the GPS recorder was not available during the collection study. All vehicles are loaded with the GTM conditions.

There are two main steps; classification of effecting parameters and collection of statistics. First step consists of defining the discrete drives to be collected from field and the second part of the study consists of determining the weight of the discrete drives in the duty cycle. The second part of the classification is a statistical study which is based on detailed trailer truck driver questionnaire results. Driver questionnaires are face-to-face surveys which targets to collect the driver usage percentages on each determined discrete drives at the classification part of the study.

Classification matrix is derived from the results of the first and second step of the discretization study. Classification matrix is a unique table for Turkey trailer truck usage, consists of the weights of determined routes and driving behavior on the routes. Once all the values on the matrix are filled, duty cycle could be generated using the cycle development methodology. The approach consists of using the classification matrix weights and multiplying with residency maps to create average field usage duty cycle.

To achieve the development of discrete driving behaviors that represent driver usage, test vehicle drivers are specially trained and collected data are analyzed on daily basis. A feedback mechanism established between driver and data analyzer to achieve more accurate, representative results.

In addition to routes and the driving behavior, seasons are important factors that affect the trailer truck usage profile. Planning drives on both summer and winter seasons increase the accuracy of the results. When analyzing engine coolant system components duty cycle, seasonal effects changes the results significantly.

## 2.1 Classification of Routes

### 2.1.1 Classification of real world route types

Public road classification and determination of routes on Turkey for trailer truck is the first part of the study. The duty cycle development methodology is based on degrading real world driving conditions into discrete events. Discretization is conducted on the road types which can be expressed as; expressway, motorway and rural, Figure 2.1. Classification of road types is done using General Directorate of Highways Traffic and Transportation Survey on Highways and face-to-face survey with experienced heavy-duty trailer truck drivers from various locations.

Motorway represents multi-carriage ways, where heavy-duty vehicles can drive up to 70-80 kph. Expressway represents dual carriageways, where heavy-duty vehicles can drive up to 80-90 kph. Rural is countryside roads with no traffic lights, pedestrians or pavements. May include driving through villages, these roads are not constructed with high quality for speed. There may be stop times or slow-downs depending on the traffic and road quality. An example of the rural route could be found on Figure 2.2. City road which is covered in motorway in this study represents no dual carriageways, lots of junctions, lots of stopping, pedestrians and pavements. There are long stop times and many slow-down and speed-up events.

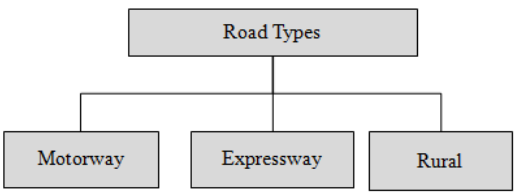


**Figure 2.1 :** Type of roads.

**Figure 2.2 :** Rural road (Route 4).

Traffic conditions, free flowing to congested, dramatically affects the vehicle speed profile. Drivers' acceleration or deceleration, gear change and engine percentage load demand significantly changes with the traffic density and road type. The development of the World Harmonized Driving Cycle study states that at the given vehicle speed, acceleration behavior of vehicles is uniform for all road types and regions. Sections with the same average speed show no significant difference in driving pattern of different vehicles and regions [2].

Determined types of roads for the study are validated with real world driver questionnaire results. Trailer truck drivers are asked which type of road they drive and the answers collected matched with the determined road types which are rural, motorway and expressway. Comparing with the Worldwide Harmonized Driving Cycle study; WHDC consists of rural, urban and motorway for Europe duty cycle determination and does not cover expressway road type [2]. Expressway plays important role at Turkey heavy duty transport routes.

### 2.1.2 Classification of real world driving behavior on routes

Driving behavior which is a function of drivers' acceleration pedal demand, brake pedal usage and gear shift characteristic is the second affecting parameter on engine duty cycle. Engine duty cycle significantly changes with driving characteristic on the same vehicle and road type. For that reason, driving behavior should be classified into categories and should be included in each discrete road type before data collection step of the study.

The first approach for the real world driving behavior classification was the combined classification using three-dimensional matrix which covers vehicle load, driving behavior and road type [6]. At Figure 2.3, classification of driving behavior as; aggressive, moderate and mild and classification of the driving style into mild, average and sporty on passenger cars can be seen. The discretization method further developed by Daimler classifying drives for commercial vehicles as; dynamic and economic [8].

In this study, on each classified road type, driving behavior is discretized as aggressive, moderate and mild. With three different road types and three different driving behavior on each road type, totally 9 combination is achieved. The clear definition of the driving behavior is needed to give necessary trainings for professional drivers to mimic the stated behavior on the field.

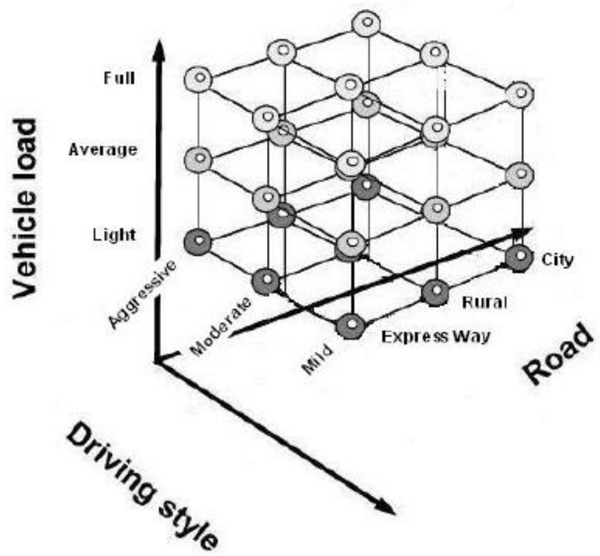


**Figure 2.3 :** Combinations of road type, driving behavior and weight [6].

Aggressive is the driving behavior remaining at high load for long periods. Driver reaches the speed limit as quick as possible, full use of wide-open throttle and full usage of engine speed and gearbox range are dominant. Driver tends to lead the average traffic flow at the aggressive drive. Moderate is the driving behavior which driver keeps with the overall traffic flow. Driver very rare uses wide-open throttle, drivers at near the speed limit where possible, can be found at Figure 2.4. Mild is the driving behavior with light use of the acceleration pedal. Driver tends to drive below the speed limit and generally slower than the traffic and lag the average traffic in this profile, keeps on the right lane, can be found at Figure 2.5. At mild driving behavior, the wide open throttle usage is not expected and driver is expected to stay at low load profile very long time with respect to total drive.

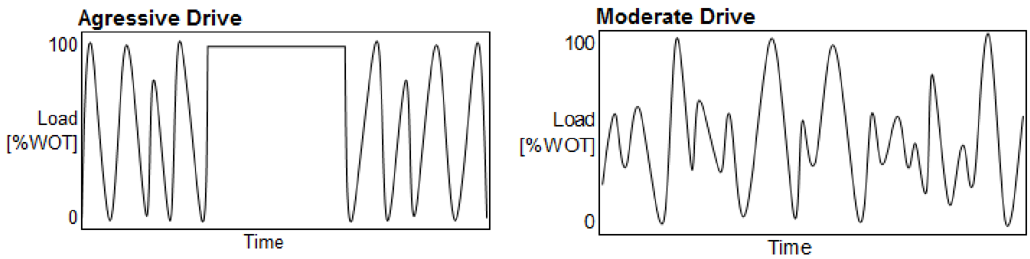


**Figure 2.4 :** Aggressive and moderate drive.

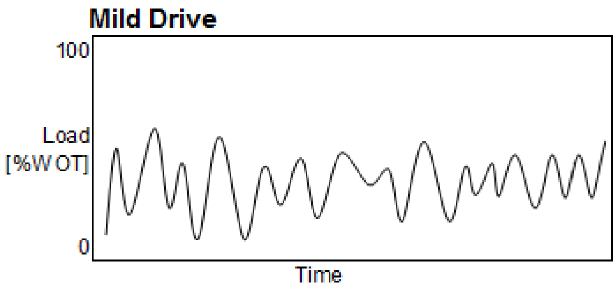


**Figure 2.5 :** Mild drive.

Professional drivers are trained to mimic aggressive, moderate and mild driving behaviors. Trial drives are conducted on each route with each driving behavior in order to control the drivers' performance and tune if needed. On data collection study, data are checked on daily basis to understand if the drivers reach the driving behavior target. Aggressive, moderate and mild drives determined comparing collected data with master drives, analyzing engine speed & percentage load residency, vehicle speed histogram and engine acceleration & deceleration residency histograms. Aggressive drive residency is much higher at high engine percentage load and high engine speed region while mild drive residency is much higher at low engine percentage load and low engine speed. The moderate drive residency at high engine percentage load and high engine speed is between the aggressive and mild drive.

Visual check from the 3D histograms is one of the useful methods to determine the driving behavior. At Figure 2.6, the average vehicle speed of the 420PS vehicle on the route 1 can be seen. Aggressive drive average vehicle speed is higher than moderate and mild, the lowest average vehicle speed is at the mild drive. Any discrepancy on the average speed profile is a sign of unhealthy data collection. For example, mild drive average speed should not be higher than aggressive drive average speed at any condition. Moderate drive is expected to have the speed that is average of mild and aggressive drive.

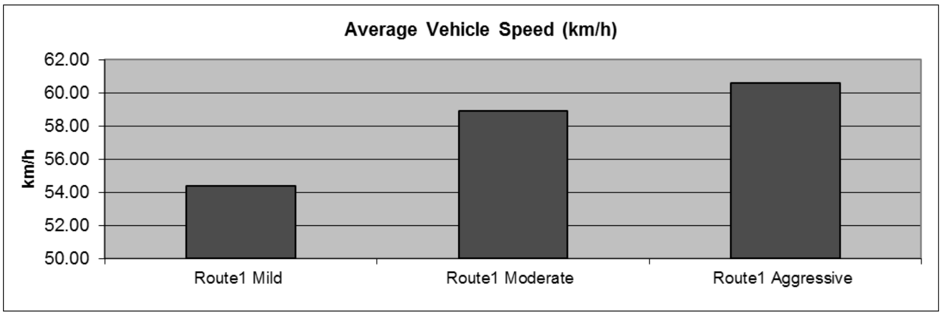


**Figure 2.6 :** Route 1 average vehicle speed.

### 2.1.3 Determination of representative routes for heavy duty trailer trucks

For each road type; rural, expressway and motorway, a public road route is determined. When choosing the public road routes; drivers of the tractor class vehicle, overall traffic conditions, road constructions, data unloading hub and the distance from driver on-off location is taken into account. Since the data logger capacity is limited with 256 MB, vehicle passed from the data import station, which is location in Gölcük, every 2 shifts or 16 hour. The data logger memory limited the maximum route distance of the study with 8 hour of driving from Gölcük location.

Routes are determined using Traffic and Transportation Survey of Highways report of the Turkish General Directorate of Highways as a main reference. Report includes Heavy Duty Total Traffic Density Map section which shows the main routes of the heavy duty vehicles and the heavy duty traffic density at stated routes, Figure 2.7. The roads with orange color indicate the heavy duty vehicle and the thickness indicates the traffic density magnitude.

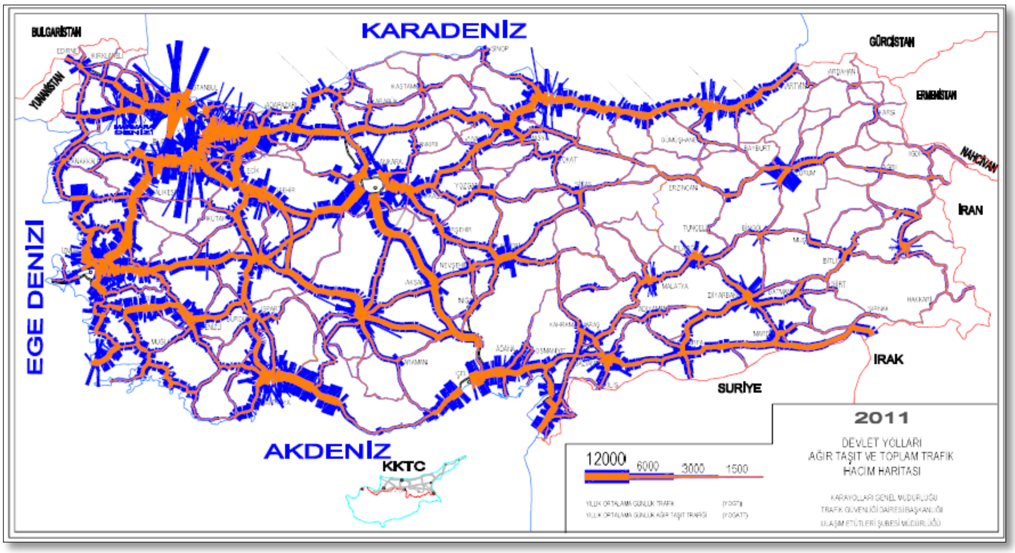


**Figure 2.7 :** 2011 heavy-duty vehicles traffic density map [6].

It is seen that density of the heavy duty vehicle traffic in Turkey are mainly at north-west region. The traffic density is not only the effecting parameter; the altitude also plays an important role on engine performance. For example, an excessive drop of ambient air pressure can lead power protection mode active on engine control unit.

In addition to the reports, trailer truck driver questionnaire results are used as a basis. The candidate routes are reviewed with professional trailer truck drivers. Considering the heavy duty traffic density map, expert views and data logger memory limit, routes are chosen as in Table 2.1.

**Table 2.1 :** Route details.

| Route | Route Detail |
|---|---|
| Route 1 - Motorway | Gölcük- Bilecik-Bursa-Bilecik- Gölcük |
| Route 2 - Expressway | Gölcük- Adapazarı- Bolu - Adapazarı- Gölcük |
| Route 3 - Motorway | Gölcük – Körfez-Orhangazi-Gölcük |
| Route 4 - Rural | Gölcük- Karamürsel- Çakırca- Karamürsel- Gölcük |

There are two different motorway routes are used in the study, the reason behind the multiple motorway usage is to cover the high heavy-duty vehicle traffic density areas of the traffic density map of General Directorate of Highways. Route 1 and Route 3 are frequently used main trade routes of the heavy-duty vehicles.

Route 1 is motorway starting from Gölcük going to Bilecik, Bursa and go back to Gölcük again. Total mileage per cycle is 600 km, see Figure 2.8.

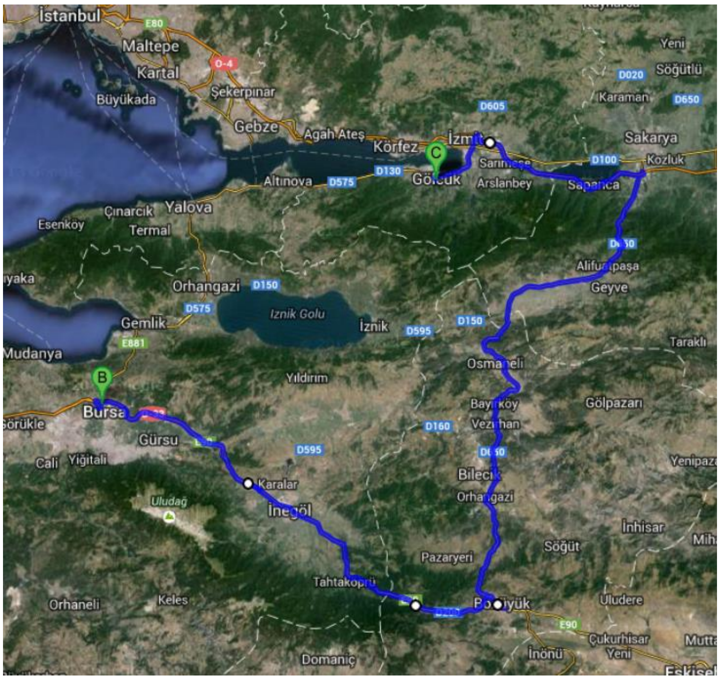


**Figure 2.8 :** Route 1 motorway.

Route 2 is expressway starting from Gölcük going to Bolu and go back to Gölcük again, see Figure 2.9. Total mileage per cycle is 500 km.

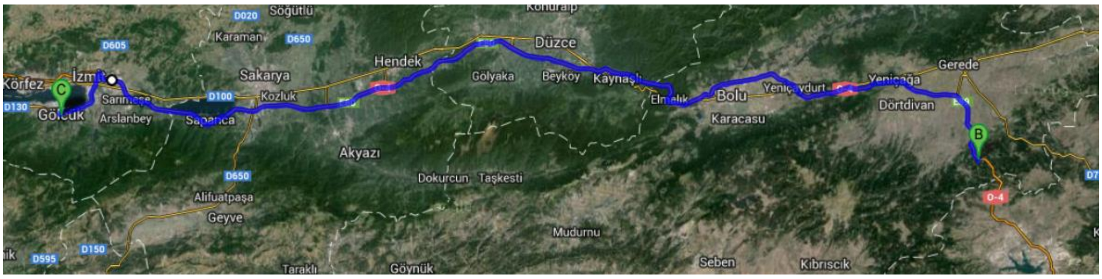


**Figure 2.9 :** Route 2 expressway.

Route 3 is motorway starting from Gölcük going to Körfez, to Orhangazi and go back to Gölcük again, see Figure 2.10. Total mileage per cycle is 250 km, 1 set consists of 2 cycles with total 450 km driving.

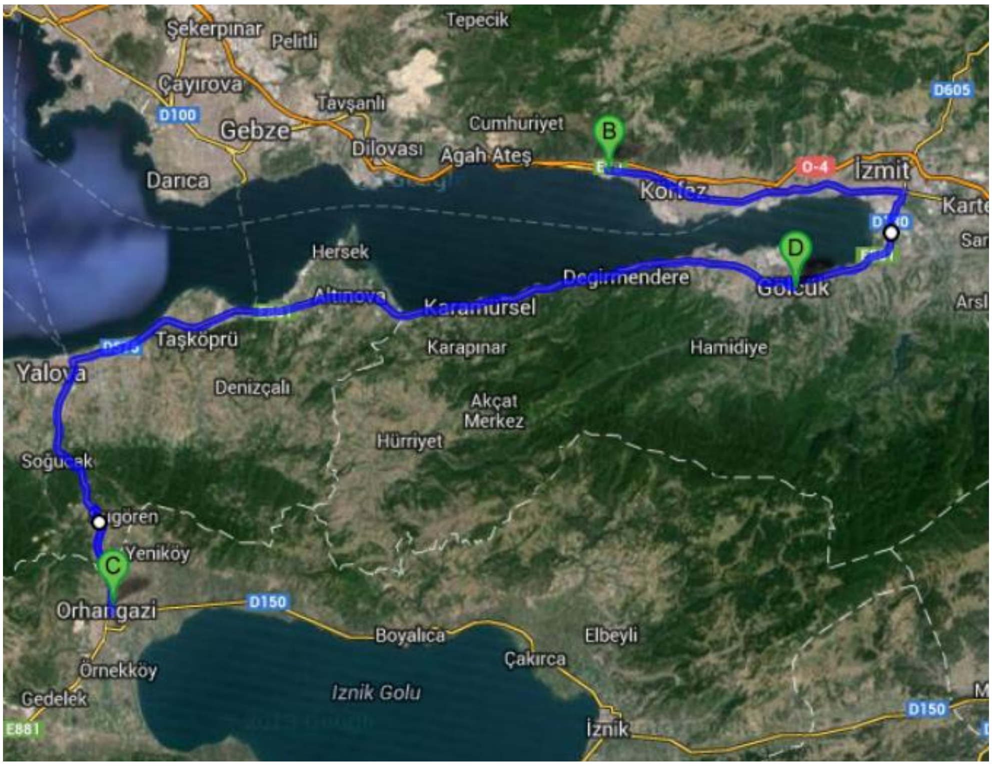


**Figure 2.10 :** Route 3 motorway.

Route 4 is rural starting from Gölcük going to Çakırca and go back to Gölcük again, see Figure 2.11. Total mileage per cycle is 150 km. The most challenging route is the Route 4, it is hard to find a rural route where heavy duty tractor with trailer can safely turn the sharp corners of the road. This road is used at good weather conditions for safety reasons. Also night drive in this route is not conducted due to limited lighting on the rural road conditions which might create danger for the driver.

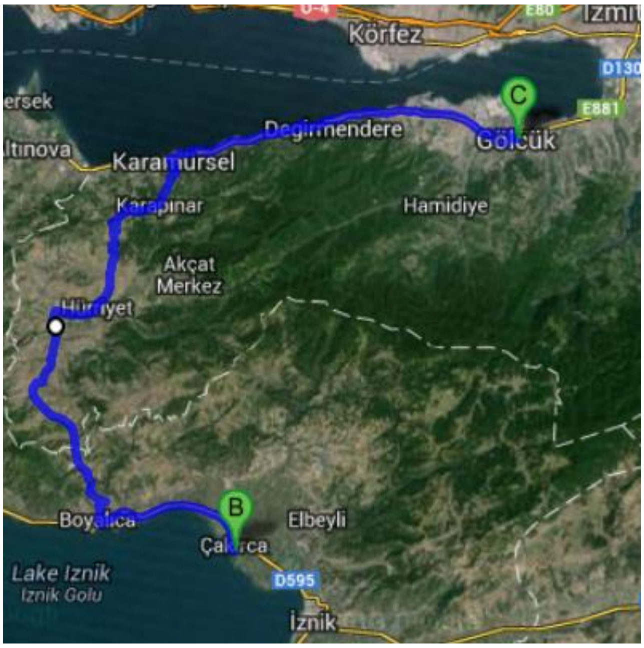


**Figure 2.11 :** Route 4 rural.

## 2.2 Test Vehicles

### 2.2.1 Trailer truck and semi-trailer details

The target of this study is to develop trailer truck engine duty cycle for Turkey driving conditions. A trailer truck is defined as a non-cargo-carrying power unit used in combination with semi-trailer [11]. A semi-trailer is a trailer without a front axle and constructed that some part of its weight is carried by trailer truck, Figure 2.12.

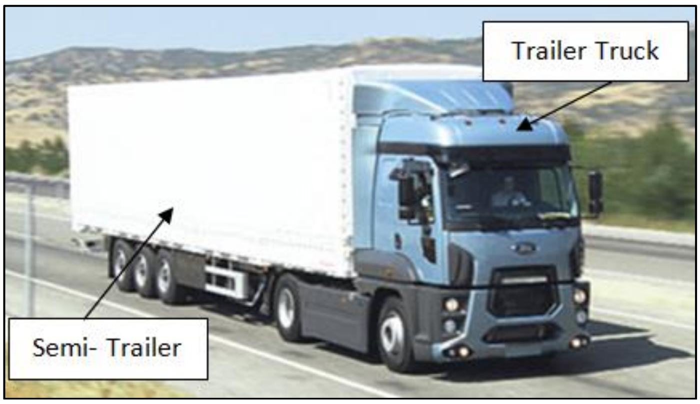


**Figure 2.12 :** Trailer truck and semi-trailer.

In order to create database of trailer truck driving data, two different power-to-weight ratio vehicles are selected. The power to weight ratio is the measure of performance of vehicle which is calculated as dividing engine power output to weight of the vehicle and it is an influential parameter on engine load and engine speed. With power-to-weight ratio from 0.79 kW/kg*100 to 0.86 kW/kg*100, long range of trailer truck classes are covered, see Table 2.2.

**Table 2.2 :** Vehicle details.

| | Vehicle 1 | Vehicle 2 |
|---|---|---|
| Engine | 10.3L 420 PS | 10.3L 460 PS |
| Maximum Torque | 1850 Nm @ 1100 RPM | 2000 Nm @ 1100 RPM |
| Gearbox | Manual | Manual |
| Power-to-weight Ratio | 0.79 kW/kg*100 | 0.86 kW/kg*100 |

Two trailer trucks are chosen as manual transmission. All vehicles are run at the specified routes with determined driving behaviors.

### 2.2.2 Driver training and reporting

In order to mimic discretized customer usage in pre-defined public routes, professional drivers are used. Drivers are subjected to class training to achieve accurate results on the routes. Vehicles are subjected to 7/24 testing on the public routes with three shifts. For every shift, different driver is used. Before the kick-off phase of the study, trial runs are made at the routes. The results of the runs are analyzed and different drivers' behavior is compared. It is found that some of the drivers were not able to mimic different usage, for example, mild drive's average speed and residency at high engine load were higher than aggressive drive for a driver. The tuning drives are run together with drivers, reliable results obtained and kick-off approved.

Before every shift, drivers filled a checklist which is very useful for further inspections on data analysis study. At the checklist, drivers asked to conduct safety checks visually, control the vehicle load, check the data logger connections and check the tire pressure. In addition to vehicle related parameters, environment related parameters are filled, for example, if the weather is rainy, drivers are asked to include this information on logbook. Aborting and skipping guidelines are prepared. The rule for catching up the aborted cycle is to continue testing in the route where the test is aborted. If events are skipped because of closed roads, driver should continue with the next event and inform the engineer. The rule for catching skipped events is to catch up all events as soon as possible with the information of engineer. In addition to checks, drivers are supplied with general driving instructions which are valid for all routes and all vehicles. Driver should never accelerate with wheel spin, never brake with blocking wheels or with the ABS system engaged. The vehicle should be driven within the limits established for highway speeds and abrupt maneuvers should be avoided. Driver should adjust speed if necessary to permit safe operation considering road, weather and traffic conditions. The maximum speed of the engine should not be exceeded and traffic rules should be followed.

At the end of the each data transfer event, presentation of data guide is followed. Vehicle driver checklist is reported with the number of routes completed during the driving time period. All malfunctions or discrepancies are encountered during the driving time period, mileage and conditions at which they occurred are reported with checklist. Components adjusted, repaired and replaced are reported. Finally, any change in route, speed, or procedure made necessary by peculiar vehicle operation or road and weather conditions on checklist are reported.

## 2.3 Field Survey

The determination of the representative routes, driving behavior and the vehicles that are used is discussed and important parameters to create a classification matrix are determined. This part of the study aims to determine the weights of discretized parameters on the classification matrix which can only be achieved by collecting real world driver usage information.

To gather driver usage statistics from the field, survey methodology is used. Survey is a systematic method for constructing quantitative descriptors of the attributes of larger population from entities which are members of the population [12]. The lifecycle of a survey consists of; planning, design and implementation steps. The planning and design steps consist of determining the critical questions to understand the driver usage, determining the target driver population and the type of the field survey.

### 2.3.1 Types of field survey

Frequently used types of the field surveys in the automotive industry are; face-to-face, phone interview and written questionnaire. There are advantages and disadvantages of the each type of survey which is expressed at Table 2.3. Depending on the application, the most suitable questionnaire should be chosen in case of efficiency and the cost.

**Table 2.3 :** Type of surveys [13].

| Type of Survey | Advantages | Disadvantages |
|---|---|---|
| Face-to-face Interview | Explain questions, explore issues, make observations, use visual aids | Expensive, need interviewer training |
| - at home or work | Accuracy, better sampling | Expensive |
| - in public places | Cheaper, more people in less time | Less representative sample |
| Telephone survey | Accurate, cheap | No personal observations |
| Written questionnaire | Cheapest per respondent | Bias from low response rate |
| - by mail | Allows anonymity | Slow |
| - by e-mail | Cheaper, quicker results | Less representative sample |
| - web survey | Quicker data processing | Need computing expertise |

The most economical type between the surveys expressed above is written questionnaire. Considering the trailer truck driver conditions, drivers' response can be low and some questions can be answered wrong due to possible misunderstanding. At written surveys, the personal observation of interviewer and response mechanism is not available. The telephone surveys have higher accuracy than written surveys and at telephone survey, respondents can ask interviewers to explain the question if not understood. However interviewers are not able to make observations and use visual aids. Face-to-face surveys are the most expensive and most time consuming. There are high logistical costs because the interviewer travels to the respondent's location. On the other hand, the data quality is higher and more accurate results can be obtained. Interviewer is physically present to answer the respondent questions. Face-to-face questions are ideal for respondents having poor reading and writing skills. This type of interview could take much time than telephone and mail interviews. The respondent usually allows interview to take their time up to one hour. This may lead to obtained more detailed and complicated answers [14].

In this study, face-to-face interview method is used; the main reason to choose this methodology is to get more accurate results regarding the level of reading and writing skills of the respondents. Data quality is the most critical item in the field surveys. Respondents can watch TV, surf on the internet or talk with someone else on other type of the surveys, at the face-to-face surveys; these options are prevented by interviewer.

As the first step of the questionnaire, candidate respondents are determined and called to take date of appointment. After the date is determined, interviewer prepared a travel plan in order to get the location of respondents.

### 2.3.2 Building survey for statistical information on vehicle use

There are two types of questions in the questionnaire; open and closed. Open questions are followed by space and do not contain any options. At Figure 2.13 an example of an open question at the survey can be found.

What is your annual mileage (km) per year?

____________________________________

**Figure 2.13 :** Open question on survey.

The other type of the question is closed questions which can be expressed as the questions where responses are included. At Figure 2.14 an example of a closed question at the survey can be found.

Did you ever drive on dirt or gravel roads?

□ Yes □ No

**Figure 2.14 :** Closed question on survey.

Drivers are asked about the road type, driving type, vehicle specification, driver profile and service items. Survey is mainly constructed with open questions. All answers are written in a paper and then transferred into digital environment for further processing.

Before asking the questions about a fact, the fact is explained to the driver by interviewer and written description is included at the survey paper to obtain accurate results. The example for road types can be found at the Figure 2.15. Face-to-face questionnaires enables to explain the topics or questions that driver does not understand.

To include descriptions for the question that can be understood differently is critical for the survey to obtain reliable results, otherwise each driver can understand different question and answer in a different way. Descriptions should be short and clear to understand.

ROAD TYPES

**Expressway** represents dual carriage ways, where heavy-duty vehicles can drive up to 80-90 kph.

**Motorway** represents multi-carriage ways, where heavy-duty vehicles can drive up to 70-80 kph.

**Rural** is country-side roads with no traffic lights, pedestrians or pavements. May include driving through villages, these roads are not constructed with high quality for speed.

**City** road represents no dual carriage ways, lots of junctions, lots of stopping, pedestrians and pavements. There are long stop times and many slow-down and speed-up events.

What percent of your mileage were driven at the routes below during the last year?

Total is 100 %.

____ % City

____ % Rural

____ % Motorway

____ % Expressway

**Figure 2.15 :** Survey question methodology example: road type

Another important thing when constructing a survey is to conduct cross-examination and include the questions in that way. The purpose of the cross examination is to understand if the interviewee answers the questions accurately.

For example, drivers are asked about the estimated annual mileage of the vehicle, after this question, in the middle of the survey drivers are asked about the total mileage and total years of operation of vehicle. The results are cross-examined and the annual mileage information that the driver is supplied is validated.

### 2.3.3 Determination of classification matrix weights

486 trailer truck drivers are asked 47 questions to obtain drivers statistics. The main questions, which are minimum number of questions required to create classification matrix, are listed at Table 2.4.

Drivers are also asked about the routes that might represent the road types that is determined in the study. Results are compared with the Turkey heavy duty truck density map and routes are optimized. In addition to routes, drivers are asked about the most frequent routes that is followed in their application. The results are analyzed and found that the drivers spend much of the time at specific routes are the members of the fleet companies.

**Table 2.4 :** Main survey questions.

| Type of Survey |
|---|
| What is your trailer truck's brand and model? |
| What is the horsepower of your truck? |
| What is the average annual mileage of your vehicle? |
| During the last year, what percent of your mileage were driven on each of these roads: City, motorway, expressway and rural. |
| Concerning the speed, at what vehicle speed do you drive the vehicle compared to traffic flow: Slower than traffic flow, faster than traffic flow, same with traffic flow. |
| Concerning the road surfaces, what percent of your mileage were driven at: Smooth roads, moderate rough roads, extreme rough roads and off-road. |

From the driver answers to the questions, percentage drive at aggressive, moderate and mild driving type and percentage drive at city, rural, motorway and expressway usage is obtained for each driver. Each driver results are listed to create classification matrix which is used at weighting the collected drives. To describe the customer statistics analyzing methodology, an example case will be followed with a sample driver A. Consider a driver A with the values at the Table 2.5 which are analyzed results obtained from survey. Driver A answered the percentages spent respect to total drive at each road and driving behavior class.

**Table 2.5 :** Example: Drive A.

| Item | Percentage Value |
|---|---|
| Aggressive Drive | 20 |
| Moderate Drive | 45 |
| Mild Drive | 35 |
| Motorway Road Type | 70 |
| Expressway Road Type | 25 |
| Rural Road Type | 5 |

With driver A's answers to survey, Table 2.5 is obtained. As explained at Figure 2.1, road types are divided into three categories and as explained at Figure 2.4 and figure 2.5 driving behavior is divided into three categories. Different 2 set of categories is converted into one set of value to create classification matrix, the result consists of 9 different categories; aggressive motorway, aggressive expressway, aggressive rural, moderate motorway, moderate expressway, moderate rural, mild motorway, mild expressway and mild rural which can be found at Figure 2.16. With combined drive methodology, it is possible to investigate the effect of different driving behavior on engine at same road type.

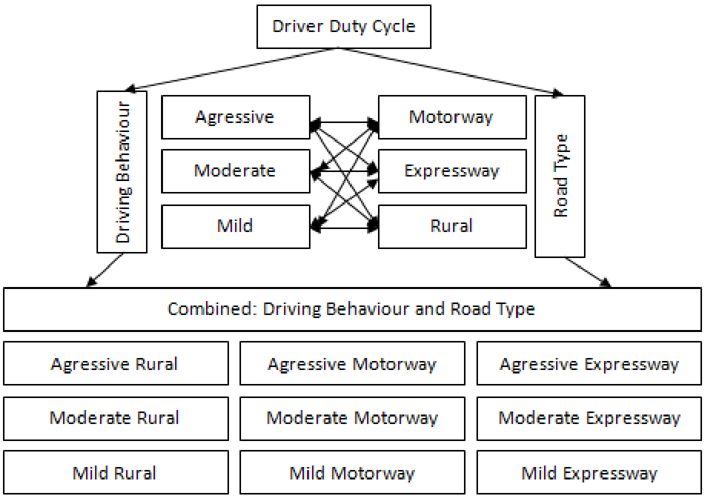


**Figure 2.16 :** Driver duty cycle schematics.

To calculate the weighted percentage of each different discretized driving category for driver A, the values at the Table 2.5 is used. The methodology consists of creating sum of each pair and has global percentage results for the driver, which can be found at Figure 2.17.

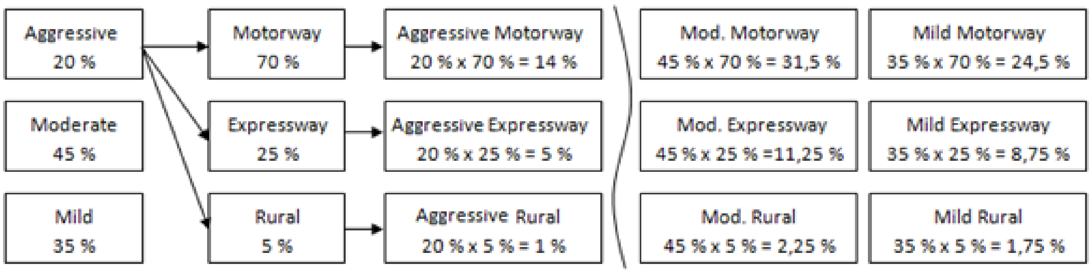


**Figure 2.17 :** Driver weight calculation example.

### 2.3.4 Development of classification matrix

After collecting statistical information from 486 drivers and determining three different road types and 3 different driving behaviors, the next step is to create a classification matrix in order to determine the weights of the each drive to develop Turkey trailer truck duty cycle. For 420PS and 460PS power variant of trailer truck vehicles, the driving profile is different but the customer usage statistics are used as same because the application and the power ratings are very close and it is not expected to have a big difference in classification matrix.

At Figure 2.18, the city, rural, motorway and expressway percentage of usage with respect to total drive can be found. The figure shows that the rural usage of the drivers' residency is relatively less when comparing with other drives. Most of the drivers at the questionnaire answered that they spend only 0-30% of total driving time in rural conditions. The city drive is following the rural drive, it is observed that the high percentile of drivers run the trailer truck between 0-30% at city driving conditions. The 20%-100% of the city drive shows bathtub curve shape. There are high end city route drivers on the questionnaire that expressed their city driving usage as 100% of the total drive. When these drivers' profile is investigated in more detail, it is found that the 100% percent city drivers are mainly using their vehicle for in-city transportation.

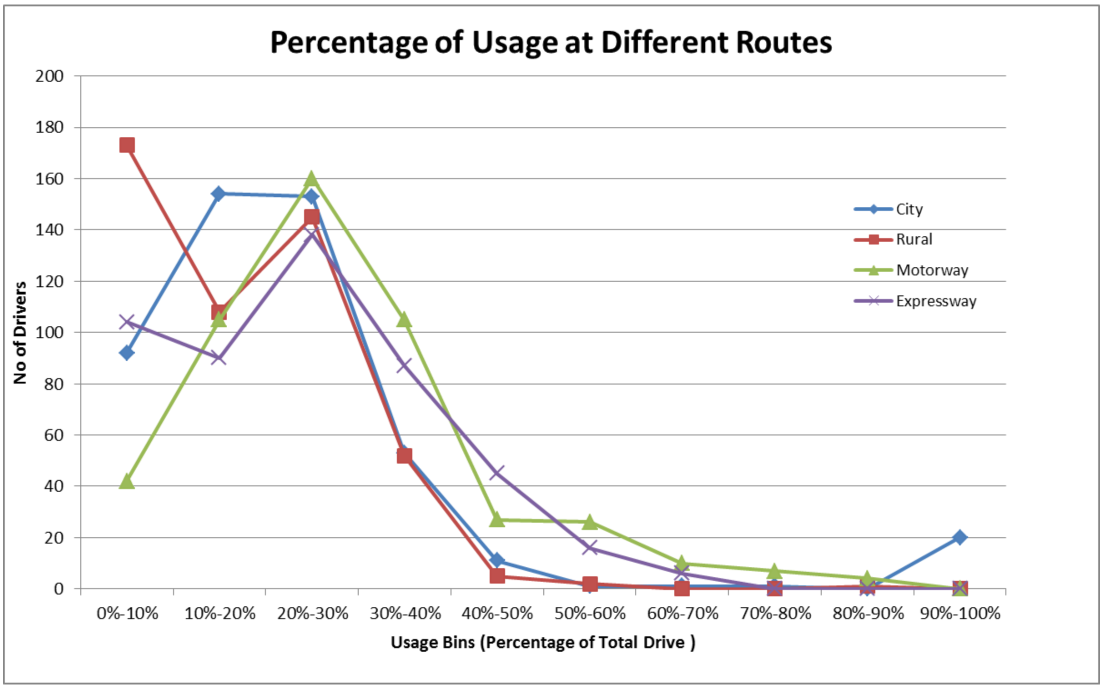


**Figure 2.18 :** Percentage usage at different routes.

At the Figure 2.18, it is observed that the high percent of the drives consist of the motorway and the expressway conditions. The number of drivers at expressway driving condition that runs 0%-10% of the total life is dramatically higher than the motorway. The frequency of the drivers that run at expressway at 0-10% and 40-50% is higher than motorway. On other regions, the motorway driver frequency is much higher especially between 20%-40%, which is resulted as expected for Turkey driving conditions. At Figure 2.19 it can be seen that the motorway usage is taking a higher percent of the total drive at Turkey trailer truck driving profile. Expressway drivers are much frequent at low usage percentage bins with respect total drive. Considering the motorway and expressway road total distance in Turkey, results are as it is expected.

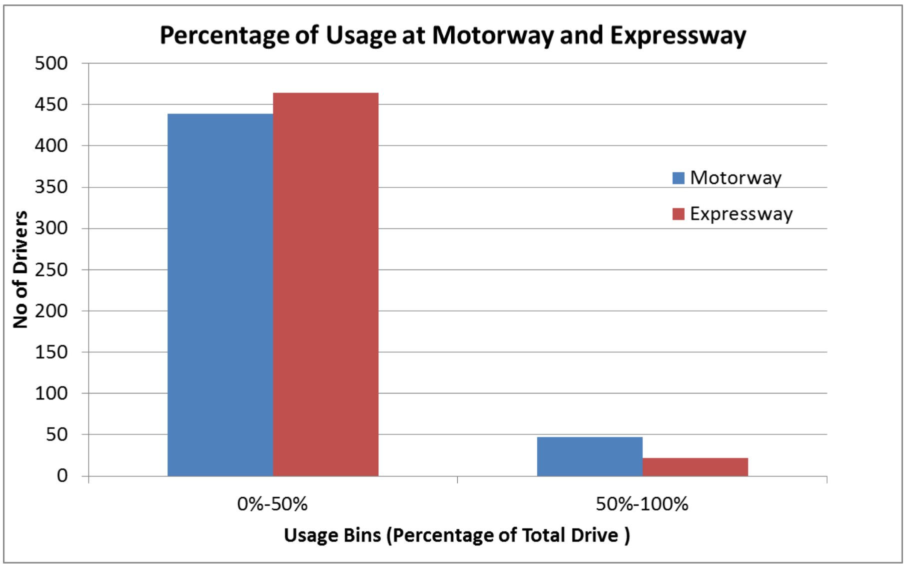


**Figure 2.19 :** Percentage usage of expressway and motorway.

At Figure 2.20 the percentage usage at different driving conditions for 486 drivers can be found. The figure contains the road types and also the driving behaviors. It is observed that for each driving condition, the percentage usage is mostly between 0 to 20 %, the higher percentage usage is not frequent. From this information it can be stated that, except the extreme drivers, an average driver does not spend more than 30 % of total drive at any driving condition. It is also observed that moderate city driving condition has relatively high no of drivers at 40-50% percentage of total drive.

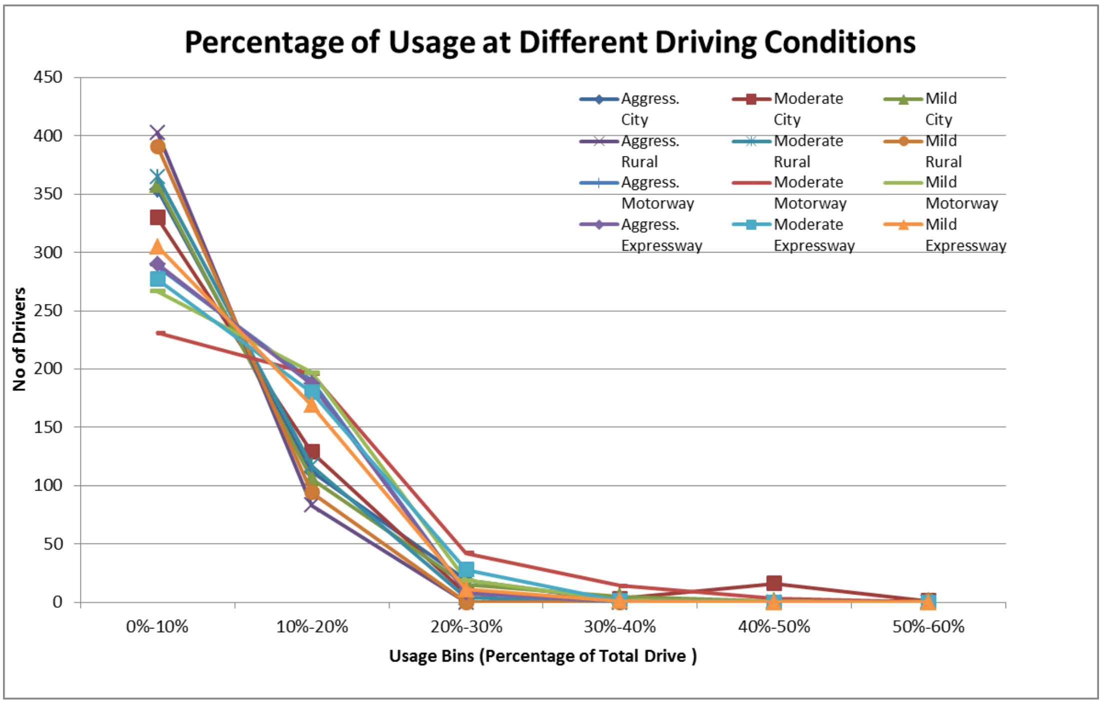


**Figure 2.20 :** Percentage usage of different driving conditions.

At Figure 2.21, the percentile plot of the different driving conditions can be found. In this plot it is seen that for the 90th percentile driver, the percentage residencies, except the moderate motorway drive, all other drives' percentile values are less than 20%. From the percentile plots, it can be clearly seen that until the 95th percentile customer, the moderate motorway residency percentage is higher than the other driving conditions. Moderate motorway drive should have the highest weight in the classification matrix. It is also observed that the aggressive rural has the lowest percent of the total drive among the driver percentile, for the trailer trucks it is not frequent that the trucks drive faster than the flowing traffic in the rural, so that low usage profile is expected. The percentile plot is a useful method to see the extreme drivers. Drives follows the same trend from 10th percentile to 90th percentile of drivers but after 90th percentile there is a sharp increase in the percentage of usage which means there is a relatively small group of drivers that run high percent of their usage. The other use of the percentile plots is to understand the quality of the questionnaire data. The percentile lines with grades that are not changing dramatically show that the drivers' response in the usage surveys can be used in the study.

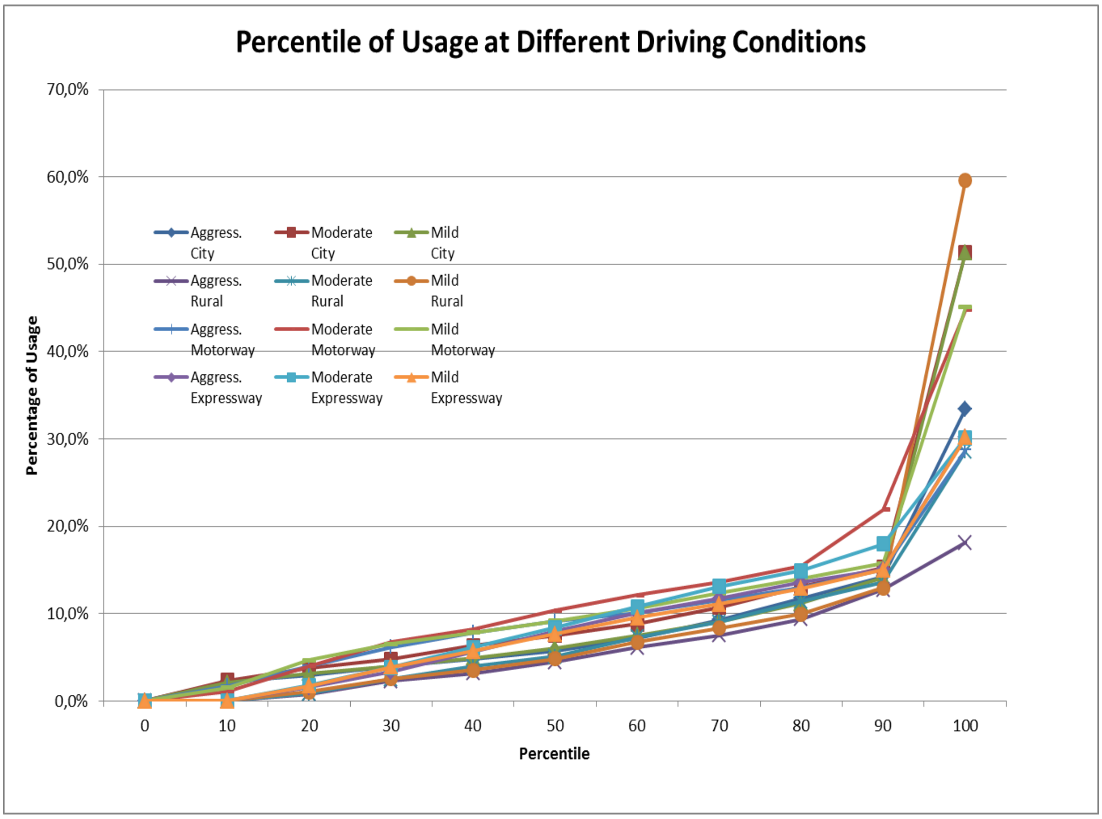


**Figure 2.21 :** Percentile usage at different driving conditions.

Using the mathematical average, percentile weighting of the driver percentile results and further evaluation with the driving experts, the classification matrix for Turkey trailer truck profile is calculated and can be found at Table 2.6.

**Table 2.6 :** Classification matrix for Turkey trailer truck profile.

| Driving Type | Weighted Percentage Value |
|---|---|
| Aggressive City | 7,3% |
| Moderate City | 9,9% |
| Mild City | 8,1% |
| Aggressive Rural | 2,7% |
| Moderate Rural | 4,0% |
| Mild Rural | 3,3% |
| Aggressive Motorway | 10,2% |
| Moderate Motorway | 14,8% |
| Mild Motorway | 11,4% |
| Aggressive Expressway | 8,9% |
| Moderate Expressway | 11,4% |
| Mild Expressway | 8,1% |

Since the city usage profile is covered in motorway in the data collection study, the table is re-constructed and can be found at Table 2.7. The duty cycle for the average driver is calculated using the statistical information at Table 2.7. It can be seen that the higher percentage of drive is present at the moderate drives where drivers run their vehicle with the flow of traffic.

**Table 2.7 :** Classification matrix for Turkey trailer truck profile (city drive modified)

| Driving Type | Weighted Percentage Value |
|---|---|
| Aggressive Rural | 2,7% |
| Moderate Rural | 4,0% |
| Mild Rural | 3,3% |
| Aggressive Motorway | 17,4% |
| Moderate Motorway | 24,7% |
| Mild Motorway | 19,4% |
| Aggressive Expressway | 8,9% |
| Moderate Expressway | 11,4% |
| Mild Expressway | 8,1% |

Classification matrix weights are calculated and listed for different driving conditions. The percentage weights change from application to application. This study covers the trailer truck duty cycle which does not work at the construction and other special application sites. At construction, garbage truck and other special applications, a separate classification matrix should be created and the matrix in this study cannot be used.

The collection of the driver statistical information on trailer truck is a challenging operation and should be repeated in order to increase the accuracy of the data. At some points, the information from the sources at the field and the information directly from the drivers do not match. An effective way for getting accurate driver statistical data is to increase number of drivers in the questionnaire and conduct the driver surveys face to face.

The classification matrix can have a separate dimension which is the weight of the vehicle. If the weight of the vehicle is included, the percentage weight values on each drive might change. If there is an intention to consider the vehicle weight in the duty cycle study, the driver questionnaire should be built in that manner that asks drives how frequent they drive on each driving condition GVM, GTM and unladen. The statistical data collection side of the study is less challenging for the vehicle weight included duty cycle development study. The challenging side is to apply the different loading on the test vehicles that is intended to mimic the classification matrix usage. Including vehicle weight factor increases the total driving time and complexity of the driving event as well as the cost of the project. On the other hand, it is seen that the effort to include the vehicle weight may not give the same benefit for powertrain duty cycle development. In this study, drivers were asked of the vehicle weight that they drive the vehicle on Turkey public road. It is observed that the 80% percent of the drivers use the vehicle loaded between the 30-40k kg and the unladen usage is not frequent at the market. Classification matrix is not expected to change with time and it is more solid than the collected data from the field. The field powertrain data changes by emission regulations, power to weight ratio, driver profile and with other effecting conditions. However the main route and residency at the routes do not change as fast as the powertrain technology and applications.

# 3. COLLECTION AND ANALYSIS OF PUBLIC ROAD VEHICLE DATA

After collecting real world driver usage statistical data and determining the weights on the different drives, the next goal is to collect data from the drives at the classification matrix. At the start of the project, the data acquisition system must be selected properly to record the required number of channels at required time period. The maximum logging period is the function of the number of channels, the measurement frequency at each channel and the total recording time. During the project it is not effective to change the data acquisition system as the lead time for the data loggers can take several weeks. For that purpose number of channels to be recorded is listed including the frequency at each channel at the start. The attention is given to the listing of channel process. Requiring high frequency measurement from the low frequency sensors, like temperature sensors, can take non-value adding memory usage. Total recording time is defined as the time between periodical data transfer events. The data acquisition system should be capable of recording data until data transfer process is completed. At each data transfer event, the memory of the data logger should be erased after the data are copied into the flash drive.

After setting the data acquisition system, shifts are planned with clear definition of the route and driving behavior. To improve the process quality, all the planning of the shifts is made considering the drivers home location, the number of days that drivers spend in night shift, data transfer hub locations and road construction events (if any planned event is present). At the planning phase care is given to include night and day conditions for all driving conditions. The traffic density and the driving profile can significantly change on the routes at the daytime and at the nighttime. In some weather conditions, for example snowy days, the night shift should not be planned at some routes like the rural because there might be a safety problem while running the vehicle at that route.

Quick response to data collection event is a critical issue. After transferring event, the data is analyzed in a fast manner if there is any failure in recording or any noise in the data. For that purpose software tools, such as MATLAB m file or Microsoft Excel Macro, can be used to evaluate the data quality and give feedback to drivers. If necessary, the driving event should be run again to obtain high quality data. Since all the duty cycle estimations are based on the recorded data, the duty cycle is very sensitive with data quality. The quality of the data should always be kept on a high level at the public road recording events.

## 3.1 Data Acquisition System

### 3.1.1 Measurement Channels

In this project, the data is collected from the vehicle bus which is the specialized internal communication network that interconnects components inside a vehicle. There is no additional analog or digital instrumentation; all parameters are recorded via engine on board diagnosis. To have instrumentation on vehicle requires another data acquisition box that increases the system complexity, the on board diagnosis data loggers are more basic, cost effective and less complex.

On board diagnosis is a computer-based system in vehicles that is designed to monitor the performance of some engine components that is responsible for controlling the emission [15]. It is a very effective tool to measure and record the powertrain related parameters. To record the selected parameters, one should have the parameter group number, data length, resolution, data range and data address.

Since this study aims to develop an engine duty cycle for Turkey conditions, only parameters related with engine are measured. 14 parameters are selected and can be found at Table 3.1 with the frequency recorded. The main parameters required to develop a duty cycle are the engine speed, vehicle speed and engine percent torque. Using these parameters duty cycle residency maps can be created. Clutch switch parameter are recorded to increase the accuracy rate of the gear calculations. There is not a gear channel in on board diagnosis system and the gear should be calculated using engine speed, vehicle speed and clutch switch. Other parameters are recorded for the future reference to enable the life calculations and the evaluation of technological applications on engine systems and sub-systems. All channels are recorded via vehicle internal communication network.

**Table 3.1 :** Recorded channels.

| Channel (Unit) | Frequency |
|---|---|
| Engine Speed (rpm) | 10 Hz |
| Vehicle Speed (km/h) | 10 Hz |
| Clutch Switch (1/0) | 10 Hz |
| Engine Percent Torque (%) | 10 Hz |
| Accelerator Pedal Position (%) | 10 Hz |
| Engine Coolant Temperature (°C) | 5 Hz |
| Engine Fuel Temperature (°C) | 5 Hz |
| Engine Oil Temperature (deg C) | 5 Hz |
| Engine Oil Pressure (kPa) | 10 Hz |
| Engine Boost Pressure (kPa) | 10 Hz |
| Engine Fuel Rate (L/h) | 10 Hz |
| Ambient Temperature (°C) | 5 Hz |
| Barometric Pressure (kPa) | 10 Hz |

Accelerator pedal position recorded to understand the power requirement profile of users at the field. It is expected to have higher pedal demand in 420PS vehicle because the power to weight ratio is lower. The temperature and pressure channels are important to develop field correlated accelerated test cycles. For example, the thermo mechanical fatigue life of cylinder head bridge area is a function of the engine torque and engine coolant temperature trend at the field. To have these parameters recorded gives critical information for the engineers at the engine development in design phase. With boost temperature trend line in the field, the calculation of the high cycle fatigue in the intake manifold due to pressure fluctuation can be calculated and the design can be improved in the prototype phase of the engine.

Since the data acquisition system has the limited capacity, the number of channels kept in 14. Measurement frequency of the pressure sensors is determined as 10 Hz and the temperature sensor measurement frequency is selected as 5 Hz. At the data acquisition system software the frequency of each channel can be configured. The high frequency measurement can decrease the total measurement time.

### 3.1.2 Data Acquisition Hardware

Data acquisition system is one of the most important elements in the data logging process. The system should support the communication protocols in the vehicle bus. Before determining the capacity of the logger, to determine the durability of the logger is a critical issue. If the data logger is used inside the trailer truck, the durability standards can be lower but if the logger is used in the engine compartment, the durability standards will be much higher. The durability standards and the cost of the data logger are proportional. There is IP rating table which is established by the International Electro Technical Commission that is used to provide an ingress protection rating for the electronic equipment, the table can be found at Table 3.2. The ingress protection rating has two digits; the first digit represents protection against ingress of solid objects and the second digit represents the protection against the ingress of liquids. A data logger in the cabin of the trailer truck can have IP54 rating. On the other hand, a data logger in the engine compartment should have IP67 standard to have durability against the dust ingress and the immersion of water for short periods of time.

**Table 3.2 :** Ingress protection table [16].

| IP | First Digit: Ingress of Solid Objects | Second Digit: Ingress of Liquids |
|---|---|---|
| 1 | Protected against solid objects over 50mm e.g. hands, large tools. | Protected against vertically falling drops of water or condensation. |
| 2 | Protected against solid objects over 12.5mm e.g. hands, large tools. | Protected against falling drops of water. |
| 3 | Protected against solid objects over 2.5mm e.g. wire, small tools. | Protected against sprays of water from any direction, even if the case is disposed up to 60from vertical. |
| 4 | Protected against solid objects over 1.0mm e.g. wires. | Protected against splash water from any direction. |
| 5 | Limited protection against dust ingress. | Protected against low pressure water jets from any direction. Limited ingress permitted. |
| 6 | Totally protected against dust ingress. | Protected against high pressure water jets from any direction. |
| 7 | N/A | Protected against short periods of immersion in water. |
| 8 | N/A | Protected against long, durable periods of immersion in water. |

In this project the data loggers are installed inside the vehicle cabin and as durability standard IP54 is sufficient because there is no level of water and low level of dust is present. It is always better to have a high durability rating data logger that might be used in outdoor environment in the future projects. In addition to IP rating, to mount data logger in the vehicle is an important issue. For that purpose protective mounting cases should be provided. Otherwise data logger connecters can be loosened because of the vibrations in the cabin and that can cause the loss of the data on the project. The load on the connectors should be minimized and connectors should be chosen as locked connectors.

Choosing a standalone data acquisition system is important in public road vehicle data activities. The presence of a portable computer is not practical and the computer takes space and requires an additional electrical charging. The standalone data acquisition systems measure and record the vehicle bus parameters without requiring a computer. Data loggers with real time clock should be preferred to record the time and date accurately with the powertrain parameters.

The software support is another important parameter when determining the optimum data acquisition system. The software should support triggering events. The trigger function allows starting and stopping the data logging event with predefined parameter ranges. Triggering events are useful to record data when engine is working and not record data when engine is not running. With trigger event, the data logging space is used in an effective manner.

The data transfer period was 16 hours in this project. At determined shift, the vehicle was transferred to data processing hub and the data recorded is transferred to the flash drive. Considering the IP standards, the number of channels required, measurement frequency at each channel and data transfer period, 256 MB OBDII data logger is selected which can be found at Figure 3.1.


**Figure 3.1 :** Data acquisition hardware.

The data loggers with removable compact flash cards can reduce the data transferring time and can increase the efficiency of testing. To transfer the data from USB to PC could take longer time; to swap the compact flash card should be preferred. With the compact flash cards, computer is not needed in the data transfer hubs and complexity can be reduced. Any complexity at the data logging process leads improper data logging activity.

In the market there are GPRS based remote access control data loggers which allow engineers to get access to data logger when the vehicle is running. This type of data loggers is very effective and saves data transfer hub waiting time but the cost of the logger is much higher. GPRS based loggers also can give warning if selected parameters value is higher than the threshold, for example the vehicle speed can be monitored and warnings can be sent to the engineers. With using the transfer of binned data, data transfer cost can be lowered. At some conditions where the internet is not available, there may be loss of the time based data if the data capturing capacity of the data logger is not sufficient.

At Table 3.3, technical specifications of the data logger can be found. ATI Vision Hub uses 15-pin Dsub connector to conduct the communication with the vehicle hub. To communicate with the computer for the setting data logger, the USB connection is used. To reach the recorded data, the USB communication or the flash drive can be used. Device temperature range is suitable for the Turkey driving conditions for both in cabin and under hood. Device power can be fed externally using a power adaptor. The other option is to connect the vehicle bus power connections to the device using the Dsub connector. With this method, there is no need to use an external cable which adds complexity to the process. External power cable can be loosed with the vibrations at the vehicle. Loosed cables can create loss of data which may result with the repeating the latest drive, so that using compact solutions accelerates the project and leads the cost reduction at the project. The device is relatively small so that to mount device on to the panel of the vehicle is possible with an external mounting unit. ATI Vision Hub also has LED indicators for communication and power status purposes. If any error occurs during the logging process, driver can see the visual LED indicator and report the problem. In some hardware applications, there is noise emitting system which gives warning to the driver.

**Table 3.3 :** Data logger technical specifications [17].

| | | |
|---|---|---|
| Configuration | Application Interface | VISION Calibration and Data Acqusition Software |
| Special Capabilities | Vehicle Network Aux I/O | 15-pin Dsub (provides access to VNI2/VNI2 + I/O) |
| Operating Conditions | Communication | High-speed ICP CAN |
| | Connectors | To PC: 1 USB connection<br>To VISION hardware: 2 B Series 5-pin LEMO |
| | DC Power | 1B Series 3-pin LEMO |
| | Power Supply | 9 to 32 VDC |
| | Power Consumption | 4W (with VNI2 Card) |
| | Temperature Range | -40 °C to +85 °C |
| Mechanical | Dimensions | 135mm x 93mm x 29mm |
| | Weight | 369g |

## 3.2 Data Collection

### 3.2.1 Planning shifts, route and driver combination

There are 9 different driving combinations on 4 different routes determined in the data collection study. Vehicles are run 24 hours at 7 days of week during the data collection event. For that purpose three different shifts are established; 08:00 to 16:00, 16:00 to 24:00 and 24:00 to 08:00. Each shift has different driver, using different drivers enables to collect driver variation characteristic which increases the representativeness value of the duty cycle. To include the driver-to-driver variation in the study, drivers in driving types is planned in a way that each driving type is run at least with two different drivers, see Table 3.4. To have the effect of the driver-to-driver variation in duty cycle increases duty cycle correlation with real world usage conditions. At data analysis, at least averages of two drives are taken in a route and driving type to include driver-to-driver variation. In some drives, more than four average is taken to increase the data accuracy and capture the variation. This process is tracked daily to understand drivers profile and change shifts if needed.

**Table 3.4 :** Load data collection plan.

| Day | Route | Driving Type | Daily Target (km) | Daily Target (cycle) | Shift Drivers Shift 1 | Shift 2 | Shift 3 |
|---|---|---|---|---|---|---|---|
| 1 | Route1 | Agressive | 1200 | 2 | A | B | C |
| 2 | Route1 | Moderate | 1200 | 2 | B | A | C |
| 3 | Route1 | Mild | 1200 | 2 | B | C | A |
| 4 | Route1 | Agressive | 1200 | 2 | C | A | B |
| 5 | Route1 | Moderate | 1200 | 2 | A | C | B |
| 6 | Route1 | Mild | 1200 | 2 | C | B | A |
| 7 | Route2 | Agressive | 1000 | 2 | C | B | A |
| 8 | Route2 | Moderate | 1000 | 2 | B | C | A |
| 9 | Route2 | Mild | 1000 | 2 | B | A | C |
| 10 | Route2 | Agressive | 1000 | 2 | A | C | B |
| 11 | Route2 | Moderate | 1000 | 2 | C | A | B |
| 12 | Route2 | Mild | 1000 | 2 | A | B | C |
| 13 | Route3 | Agressive | 900 | 2 | A | B | C |
| 14 | Route3 | Moderate | 900 | 2 | B | A | C |
| 15 | Route3 | Mild | 900 | 2 | B | C | A |
| 16 | Route3 | Agressive | 900 | 2 | C | A | B |
| 17 | Route3 | Moderate | 900 | 2 | A | C | B |
| 18 | Route3 | Mild | 900 | 2 | C | B | A |
| 19 | Route4 | Agressive | 600 | 4 | C | B | A |
| 20 | Route4 | Moderate | 600 | 4 | B | C | A |
| 21 | Route4 | Mild | 600 | 4 | B | A | C |
| 22 | Route4 | Agressive | 600 | 4 | A | C | B |
| 23 | Route4 | Moderate | 600 | 4 | C | A | B |
| 24 | Route4 | Mild | 600 | 4 | A | B | C |

Recurring night shifts for the drivers were avoided to increase the driver efficiency. Getting feedback from drivers is getting harder if the driver works on the night shift during the whole collection study. Another important issue about changing the night shift drivers is the safety concerns, changing truck drivers increases the attention. Nights shift drives tracked very carefully to avoid safety issues.

During the data collection event, some routes may not be completed as targeted. If target mileage is not achieved, re-run at the planned cycle can be conducted. There may be some unplanned activities such as road constructions or other events which do not allow planned routes to be run, in that cases, revision of the load data collection plan need be prepared.

### 3.2.2 Data upload and collection

The data transfer period of collection study is 16 hours. At every 16 hours, vehicle is entered in the collection hub to take the recorded vehicle bus data and switch the device memory to get the device ready for the next cycle. Data collection event is completed with laptop via memory card. After data is collected, it is transferred to a flash drive and taken from the field for first analysis. If data storage limit is exceeded during the collection event, the system overwrites the upcoming data on the collected data and there is loss of information which is not desired. To prevent the data loss, a memory trigger is defined. If memory exceeds a critical limit, system activates the red led lamp on the device so that driver can understand that the data logger is reaching its memory limit.

Another important issue at data transfer is the file format. A widely used file format such as the txt is very common at vehicle data logging applications. The special file formats that can only be opened with specific data logger software must be avoided. In future investigations, there may be some computers that have not got the specific software to open special file formats. If special file formats are used, the data should be later converted to common file formats. The txt file format can be read by wide number of software and it is a practical way to keep the data.

Setting the data logger after data transfer and controlling the recording parameters are critical. At every data transfer event; time, date and the on board diagnostic file on the device should be checked. There may be some cycles that are not recorded because of human errors such as forgetting to set the data logger. To minimize the human based errors, every operation is written in a checklist and hardcopy of the checklist is used at data transfer events. Another way to minimize the human errors is to have the high memory capacity data loggers. With high memory space, the data collection interval can be increased so that number of re-setting the device can be decreased.

### 3.2.3 Importance of data check on daily basis

During data collection study, it is necessary to check the collected data on pre-determined time intervals. The driving data should be checked for two purposes; the first purpose is to control if the data is collected without any noise through intended cycle time and the second purpose is to control if data meets the targeted driving behavior. If the measurements are not checked on daily basis and an error during the collection cannot be determined, there may be huge loss in collected time based data.

Noises in the collected data may occur because of the potential electrical connection issues due to vibration in the vehicle or electrical interferences. In some cases, there may be vehicle bus related noise problems. The noise at the data logging system such as spikes can be determined by writing custom codes that tracks the delta of the signal values. On every data transfer event, data health check is conducted to avoid the loss of data. Another issue is to observe if the driver meets the targeted driving behavior, for that purpose a custom code ran on the collected data and compared with targeted reference values. At all checks, full change permission of the drive data is not given to computer codes and at all phases, human control is conducted to increase the study accuracy level.

With recurrent data checks, any unplanned vehicle stop, running the vehicle at a speed above the speed limits and unplanned actions can be determined.  During the study a feedback mechanism between engineer and drivers are established so that data check results can be shared with drivers quickly and necessary actions can be taken. At every dayshift, drivers are provided with hard copy of instructions about the last drive that is made if the last drive has data health problems. Data health problems tracked in an accurate way.

In addition to data quality at the data collection study, the engine health is checked while data analysis is ongoing. Engine related recorded channels such as engine oil temperature, engine coolant temperature and engine intake manifold temperature values are controlled to understand if any abnormal engine running conditions are present. Increase in engine coolant temperature above the desired limits is a sign of malfunction at the coolant system at the engine side or at the vehicle side such as fan or the radiator. The engine should be run without any failure in the system to characterize the duty cycle in an accurate way. Sensor values from the engine are also controlled if any abnormal values which can‘t be read at the normal engine running conditions are recorded. If engine run in derate conditions resulted from a failure mode not related with usage, the engine percentage load values will be lower and study will not represent the real world usage.

### 3.3 Data Analysis

#### 3.3.1 Data processing and cleansing

Data from 10.3L 420PS and 10.3.L 460PS vehicles are collected from the field. The total amount of collected raw data is 18 GB. To handle and process the huge amount of data, MATLAB software is selected because of the ability of fast data processing, easiness of writing custom codes to analyze data and reliability of the program.

The first step was to determine the data storage methodology. For each driving type 1x1 data structure is prepared and named as Result. The Result structure includes a double numeric data, cell data and structure data which can be found at Figure 3.2. To build data structures is an effective method which allows investigating and analyzing data easily. To take only values, to read only headers or to read only a trip's value is more fast and easy than having a single numeric data matrix.

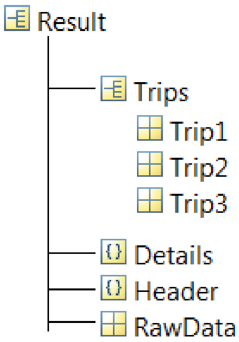


**Figure 3.2 :** Data store structure.

Definition of the trip is the drive between engine and vehicle is stopped. On each time engine is stopped, the code routine detects and creates a new trip under the Trips structure. Each trip at Trips structure is double numeric value with a number of columns equal to the number of columns in the Header cell array. Details cell array contains the date, route, driving style and shift number. The values at Details cell array is entered into the code before running the routine so that in the future data investigation, the details regarding the driving can be found under Details. Header cell array contains the headers and units of the collected data from the field. In addition to recorded channels, there is a timestamp channel which is added by data logger automatically. Total number of headers in the Header cell array is sixteen. Raw Data double numeric value matrix contains the time based measurement of the data collective.

The presence of data anomalies in the data collection study was checked during the regular intervals. The type of data anomalies that can be observed at the vehicle bus data measurement are the intermittent noise spikes and the temporary signal dropouts. The spikes occur when cables in the system does relative motion, the spikes can be detected by analyzing the time domain data. An example of spike can be found at Figure 3.3. Engine coolant temperature data cannot increase 41 °C in a second and decrease 41 °C in a second again. The high difference in a very short of time shows that this is a data anomaly and there may be an issue with the cables connecting to the temperature sensor or on the data logger side of the system. At data analysis part, the spike is detected tracking the difference at the values over the time and the two end of the spike is interpolated. The other anomaly is the temporary signal dropout; at this condition sensor value suddenly drops into the zero level in a short period of time. Signal dropout can be related with the electrical harness or connections in the system and should be carefully inspected.

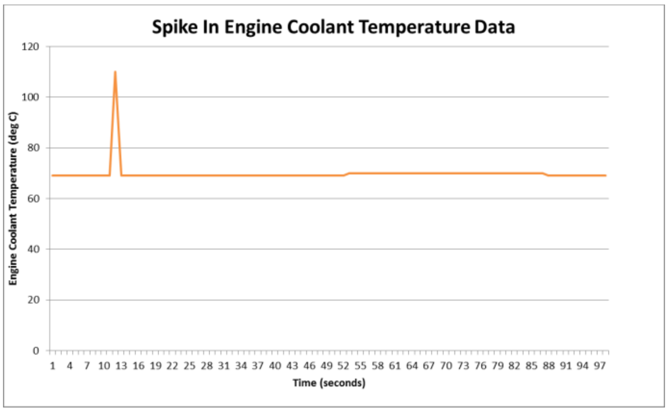


**Figure 3.3 :** Spike in engine coolant temperature data.

The code written for the spike detection takes difference of each channel at each time step. If the difference exceeds the pre-defined upper and lower bands, the code outputs the time of the possible anomaly and the data at the channels on that time. Fully automated data anomaly removal is not used at this study due to possibility to loss of data. Each reported possible abnormality visually inspected and the decision is made by human. Human based data anomaly control can take longer times but the quality of the data is getting higher with a human control. Time based trend also plotted for selected channels at each driving type to check the health of the data. Data health check is also conducted to track the status of the data logger and the cables for any possible malfunction at the system.

### 3.3.2 Determination of driving behavior

Drivers are instructed to run the vehicle at desired driving behavior during the related shifts. In addition, specific trainings are given to the drivers to mimic the intended usage, however during some cases it is found that the driving behavior target is not met and different profile was run at the shift. Duty cycle methodology is sensitive to driving behavior and any mistakes in the process should be strictly avoided. For that purpose, analysis of the drives is conducted to check if the target is met. To conduct the analysis, driving behavior should be defined in a metric way. The aggressive, moderate and mild drives are defined in a non-metric way such as driving at high load or driving at high speed which can be found at Section 2.1.2. Following parameters are selected to determine the type of drive; average vehicle speed and percentage residency at high engine percentage load above 80%. After the study, for each drive, the parameters are calculated and listed as a table for 10.3L 420PS and 10.3L 460PS vehicles to understand if the drives are run in correct way. Before the parameter listing study, after each data transfer event, the usage profile of the data visually checked plotting the engine speed and percentage load residency maps.

At Figure 3.4 and Figure 3.5 route 2 moderate and route 2 mild drive residency plots can be found. The high percentage load drive has much higher residency at moderate drive which can be seen at a glance. In definition of moderate drive, it is stated that acceleration pedal demand should be higher so the results correlated with the expected value.

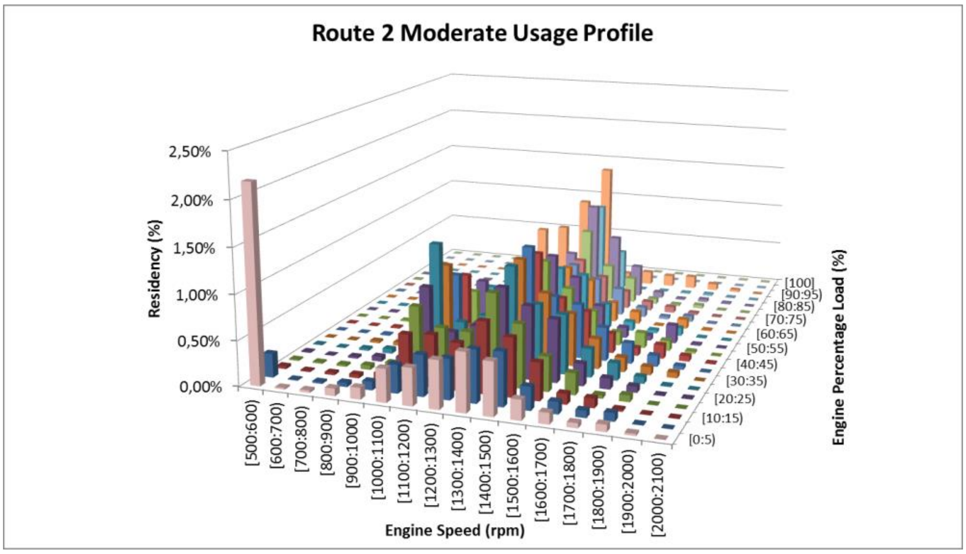


**Figure 3.4 :** Route 2 moderate usage profile for 460 PS vehicle.

Route 2 mild drive has higher percentage of residency at middle area of the engine speed and the engine percentage load axis as expected. Mild drives engine speed and percentage load residency is generally higher at the middle of the two axes. There may be outliner data but the residency of the outliners should be much lower. Another other important parameter to analyze is the engine speed. Moderate drive is expected to have higher residency at higher engine speed when comparing with the mild drive. At the residency plots, it can be seen that the route 2 moderate drive has higher residency at high engine speeds.

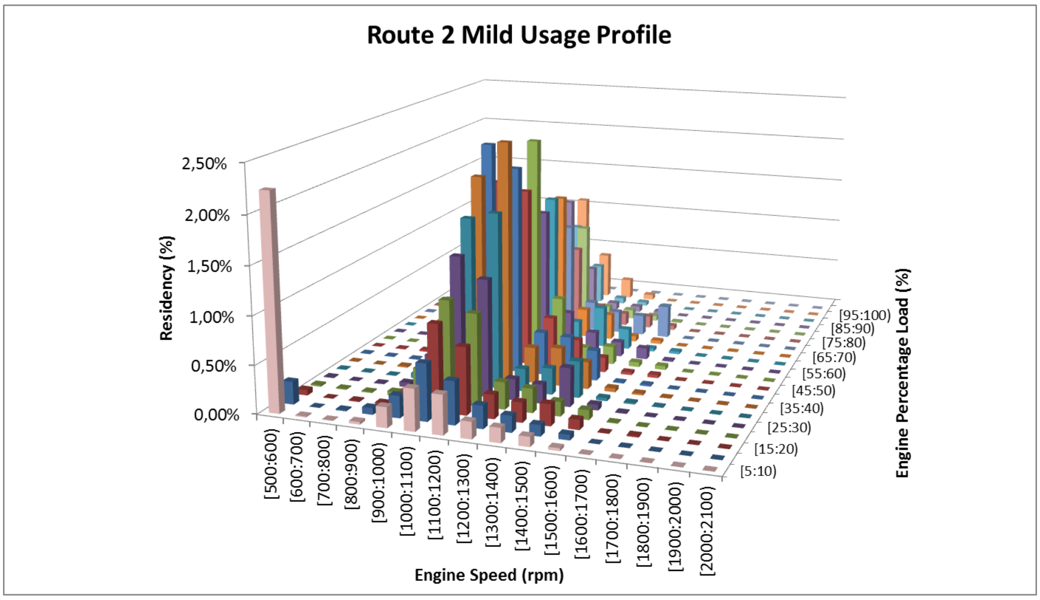


**Figure 3.5 :** Route 2 mild usage profile for 460 PS vehicle.

To determine strict mathematical definition for the aggressive, moderate and mild drive may not be accurate. During data collection study, the usage profile from the field is not known and at every application the gap between the parameters of driving behaviors may subject to change. To give specific bands for the selected parameters is practically not efficient because to predict the bands may not be possible and bands are subject to change on each application. However to list the selected parameters and compare the results gives a systematic approach which leads more accurate results.

This study aims to develop a duty cycle for trailer truck general applications. At some specific conditions like construction, mixer and other type of special applications, driving behavior should be re-defined and using the aggressive, mild and moderate may not be applicable. At some special applications like mine construction trucks there may not be several driving behaviors so that methodology change should be considered.

### 3.3.3 Gear calculation methodology

In the vehicles at this study, the gear information is not fed to the vehicle bus. To investigate the gear residency characteristic at the field, the gear channel should be separately calculated from the other parameters. In duty cycle studies where the time based gear information is accurately needed, an external sensor may be used to record the vehicle gear.

Gear of the vehicle is calculated time based and added to the recorded data as a calculated channel. To determine the gear of the vehicle, the following parameters should be collected; vehicle speed and engine speed. In addition vehicle acceleration will be calculated using the vehicle speed. To calculate the vehicle acceleration the Formula 3.1 is used.

$$\text{Vehicle Acceleration} = \frac{\text{Vehicle Speed at Time 2-Vehicle Speed at Time 1}}{\text{Time 2-Time 1}} \qquad \textbf{(3.1)}$$

First step to calculate the gear ratio is to divide vehicle speed to engine speed which can be found at Formula 3.2. The gear ratio only calculated if vehicle speed is higher than 0, the engine speed is higher than 550 rpm and the vehicle acceleration is higher than 0.

$$\text{Gear Raw Ratio} = \frac{\text{Vehicle Speed}}{\text{Engine Speed}} \qquad \textbf{(3.2)}$$

The next step is to count the frequency of each gear ratio, if any gear ratio frequency is under the 3 % than those gear ratios are removed from the calculation in order to avoid the discrepancies. Gear ratio occurrences are plotted and for each gear ratio an interval is defined. To determine the intervals 0,2 % of positive and negative band is used.

In the calculation it is observed that at some conditions gears are changing less than 2.5 second which is physically not possible. To avoid any discrepancy at gear calculation because of this problem, moving window filter is used. The moving window filter method filters the 2.5 second period all over the data and corrects the gear ratios. An example of the methodology can be found at Figure 3.6. To get to the gear 4 and turn back to the gear 3 within the 2.5 seconds is not possible, so that the gear raw ratio is changed with previous gear ratio. Using the moving filter window method, all the time based gear raw ratio values are corrected.

| | GearRaw Ratio | Gear Ratio |
|---|---|---|
| | 2 | 2 |
| | 2 | 2 |
| | 2 | 2 |
| | 3 | 3 |
| | 3 | 3 |
| | 3 | 3 |
| | 3 | 3 |
| Less than 2.5 Second | 4 | 3 |
| | 4 | 3 |
| | 4 | 3 |
| | 3 | 3 |
| | 3 | 3 |
| | 3 | 3 |
| | 3 | 3 |
| | 3 | 3 |

**Figure 3.6 :** Moving window filter methodology.

# 4. DEVELOPMENT AND CHARACTERISTICS OF DUTY CYCLE

With collecting Turkey trailer truck driver usage statistics and converting the survey answers to the residency percentage of determined drives, the data collection study is completed. With 10.3L 420 PS and 460PS vehicles, engine related parameters from vehicle bus are collected at 9 different drives with various drivers. The data quality is checked and driving behaviors controlled in each determined time interval.

The next step is to use the field survey data and collected in-use driving data to create Turkey trailer truck driver usage profile. For that purpose discrete based duty cycle generation methodology is used. Duty cycle is expressed as engine speed versus engine percentage load residency over the life of the vehicle because this study targets to develop an engine duty cycle. The main effecting parameters to engine components are the engine speed and engine percentage load.

The methodology in this study targets to create duty cycle for both prototype vehicles that OEMs are developing and also for the vehicles that are in serial production. To develop duty cycle for both cases, discretization of the real world usage conditions are conducted and different driving types and routes are determined. Using statistical data from survey results, an average duty cycle for each application is created.

Collecting data from real world users have some advantages. To catch the unexpected events in the field that the drivers can conduct is possible in this case. The various weather conditions, different route and loading conditions can be covered too. The methodology in this study is advantageous to develop duty cycle for prototype vehicles because it is not possible to take data from real world users if target vehicle is in prototype development phase. On the other hand, the estimation of the duty cycle in this study is too sensitive to the drivers, routes selected, driving behaviors, user survey results and different weather conditions. For the product development departments of the OEMs, it might be useful to correlate the discrete duty cycle development methodology with the results of real world usage methodology. To conduct this study, the vehicle should get on the serial production phase and the user data at the field should be collected. After the data analyzed, the quality of the discrete based estimation can be calculated.

Another advantage of the discrete duty cycle methodology is that engineers can conduct design of experiments to investigate the effect of different driving types on the duty cycle. At real world usage duty cycle methodology, it is not possible to change driving characteristic and conduct design on of experiment.

## 4.1 Duty Cycle Generation

### 4.1.1 Duty cycle generation methodology

Duty cycle is generated following the three important steps; collection of the real world usage statistics, creating the classification matrix and collection of real world usage discrete drives. At Figure 4.1, duty cycle development process flowchart can be found.

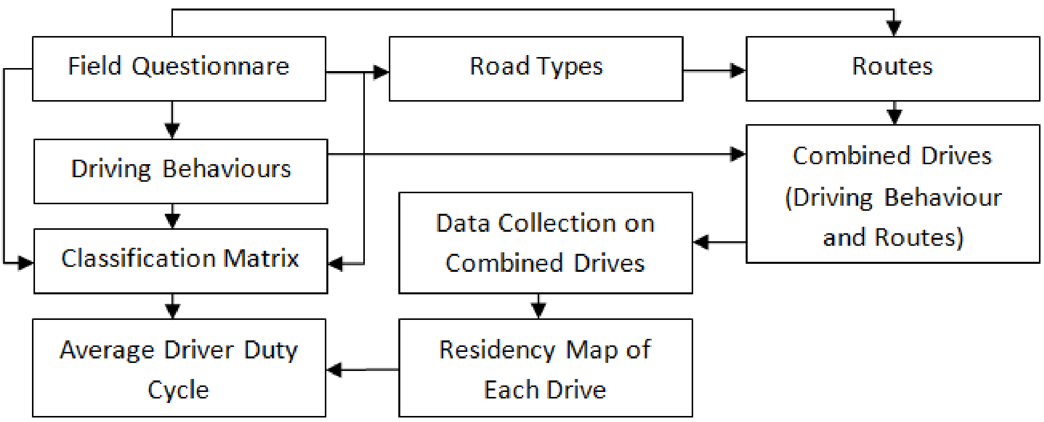


**Figure 4.1 :** Duty cycle development process flowchart.

In this study, to understand the Turkey trailer truck drivers' usage discretization method is used. Data from the each discrete drive is collected and the weight of the average customer on each drive is calculated so that combining the discrete drives with the weights, complete driver cycle can be created. This method is cost effective because for each application, data is collected from only a vehicle and the discrete methodology provides progressive accuracy with the increasing number of questionnaires. Number of drivers evaluated is up to thousands or more with further driver surveys. In this method, it is possible to collect data from vehicles at prototype phase. On the other hand, roads and seasonal effects are restricted with the methodologist consideration.

At the other common methodology which aims to understand driver usage by collecting data from real world driver vehicles, the number of drivers evaluated are restricted with the number of data loggers. This method is much more expensive and collecting real time continuous data is not possible at sufficient sample rate for a long period. Data can only be real-time tabulated and collected after a period. On the other hand this method covers many unexpected roads and seasonal effects can be encountered at the field. On the real world customer methodology, it is not possible to collect data from vehicles at the prototype phase.

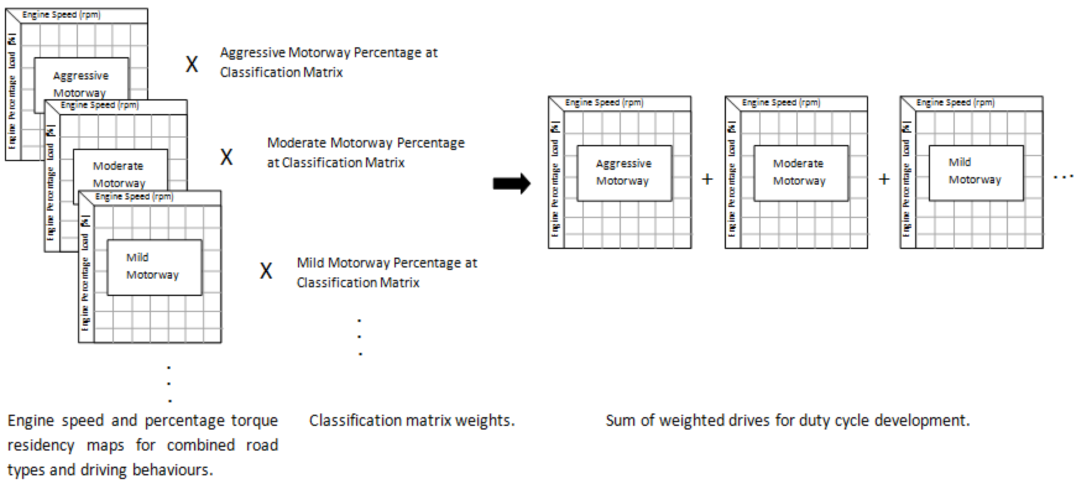


**Figure 4.2 :** Duty cycle development steps.

At Figure 4.2, duty cycle development steps can be found. Only the motorway drive is included in figure, the process is repeated for all driving types and results are summed up. Engine speed and engine percentage torque residency maps in hours for combined road and driving behaviors are calculated for a ramped up mileage value for all drives. The purpose of ramping up all the drivers to a specific value is to convert the z axis unit in the residency map to percentage value at the next steps. Maps are listed and all values in the maps are multiplied with the percentage value at the classification matrix. With multiplication, the discrete drives of the average driver are obtained. After this step, weighted residency maps of 9 different drivers are summed up to obtain the duty cycle. At last step, the residency values at the z-axis of the map which have the hours as unit are converted into the percentage values by diving all single values to sum of the total hours in the map. By completing all steps, the duty cycle of Turkey trailer truck is obtained. With this methodology the number of start at cold condition and number of transition between specified engine parameters can be calculated for an average and high percentile driver. It is also possible to count damage with defined engine damage model.

In addition to the duty cycle of the average driver, the driving profile of each driver in the questionnaire can be obtained using the development steps. The classification matrix weights can be changed with each drivers answers and the estimated drive of the each driver can be calculated. This process creates opportunity to evaluate the specific cases such as to investigate the driver profile which uses the engine at the highest load region very frequent.

The other opportunity is to understand the contribution of the each drive into the average duty cycle. The drive weights can be changed to create different duty cycles to understand the results if any of the drive could have higher percentage weights. With this approach, contribution analysis can be conducted and component development at product development phase can be leaded by different possible scenarios.

### 4.1.2 Duty cycle analysis results

Duty cycles for 10.3L 460PS and 10.3L 420PS vehicles are calculated following the duty cycle development methodology steps, the residency maps of engine speed and engine percentage torque are created.

For 10.3L 460PS vehicle, it can be seen that the high residency areas are at idle, very low load region and high load region. The idle time of the vehicle is the 6,42 % of the total drive at 460PS and at 420PS vehicle, idle time takes 7,74 % of the total driving time. It can be observed that the 460PS duty cycle has much wide distribution at the engine speed interval while the 420PS duty cycle has a narrower distribution. The engine percentage load at 0 to 5 % region has the highest residency when compared with total drive. It consists 35 % of total drive at 460PS engine and takes 29,6 % of total drive at 420 PS engine, see Figure 4.3 and Figure 4.4 for further detail. No load drives includes the gear shifting events and overrun events where vehicle goes without throttle. In heavy-duty vehicles the 0 to 5 % bin also includes the engine braking event where there is no fueling. No load drive is critical for injectors, which are cooled by the fuel injection, if the engine has an exhaust brake application.

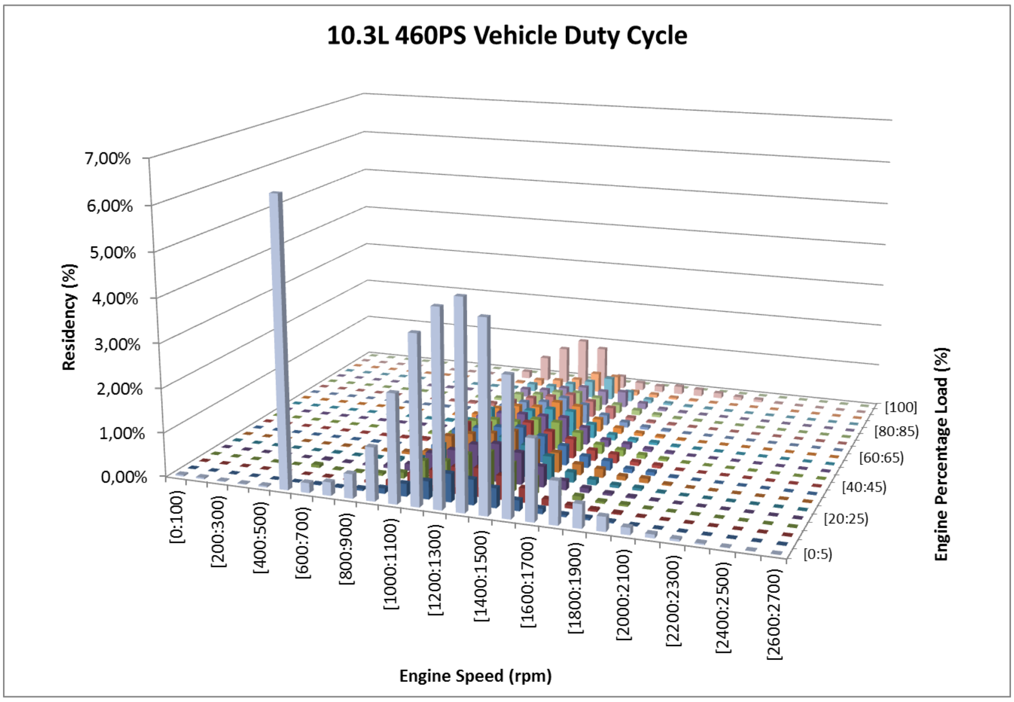


**Figure 4.3 :** 10.3L 460PS vehicle duty cycle.

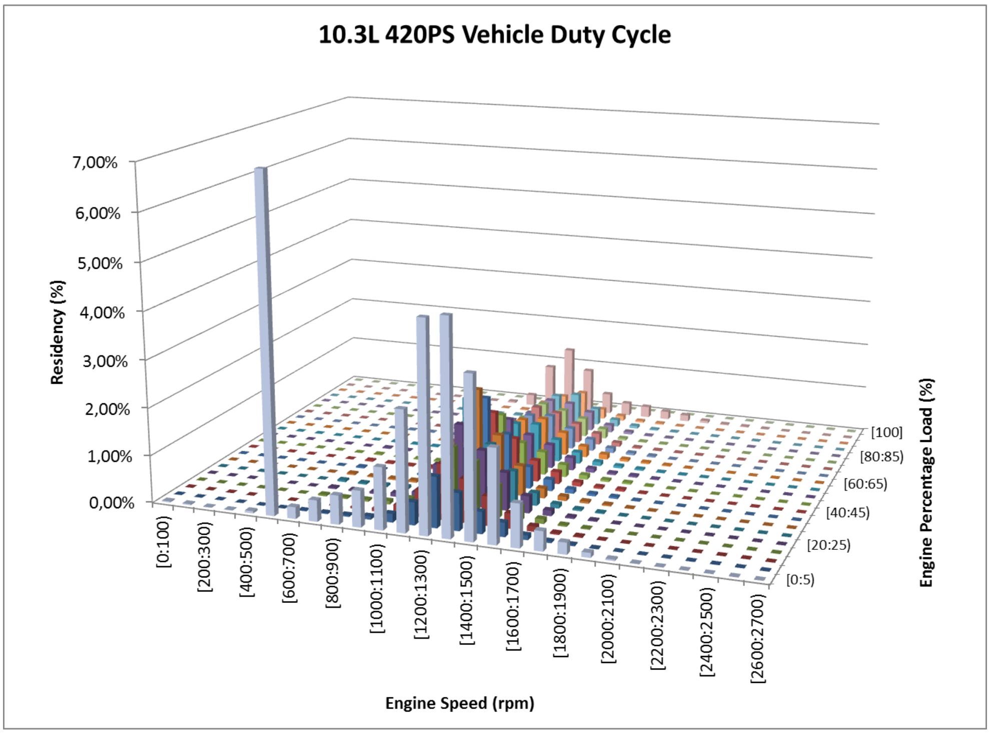


**Figure 4.4 :** 10.3L 420PS vehicle duty cycle.

Engine speed is not widely distribution at two different vehicles; it is falling between 1000 rpm to 1800 rpm. The residency after the 1800 rpm is very low compared to the residency between 1000 to 1800 rpm. At Figure 4.5, engine speed residency distribution can be found. Engine speed residency of 10.3L 420PS vehicle is higher between 1100 to 1400 rpm.

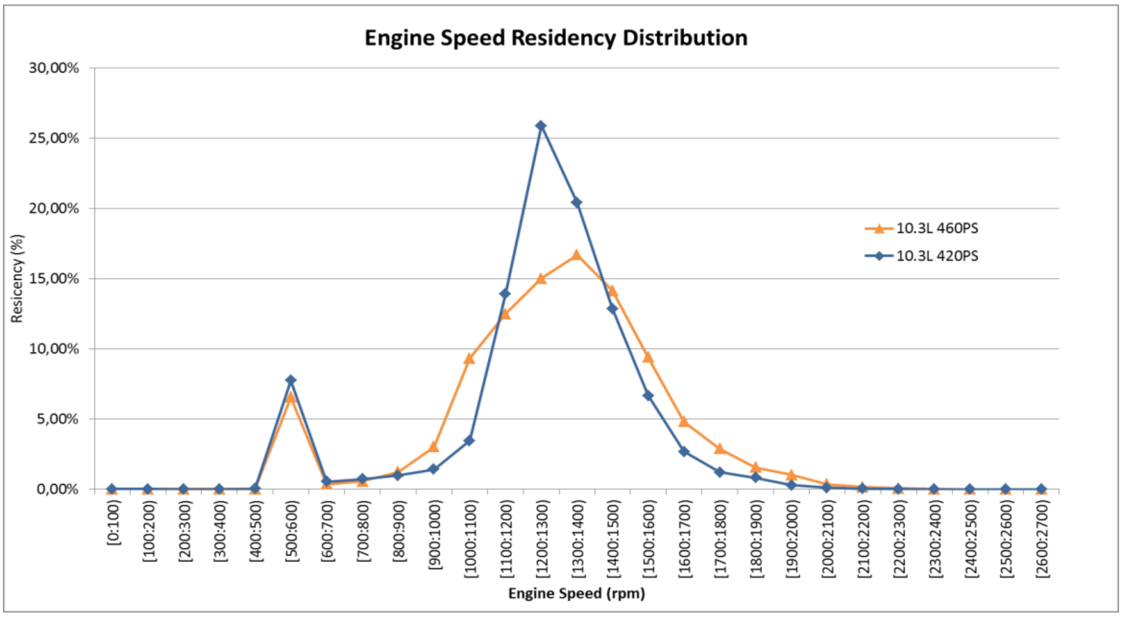


**Figure 4.5 :** Engine speed residency distribution.

At Figure 4.6, engine percentage load residency distribution can be found. The residency at 5 to 100 % engine load is between 2 % to 6 % at the duty cycle. In case of engine percentage load there is not a major difference between 10.3L 460PS and 10.3L 420PS vehicles. On the other hand, at 0 to 5 % engine load, the difference between the residencies of the vehicles is nearly 5 %.  Residency at the engine load 95 to 100 % percent is much higher than the engine percentage load values between 40 to 95 %.

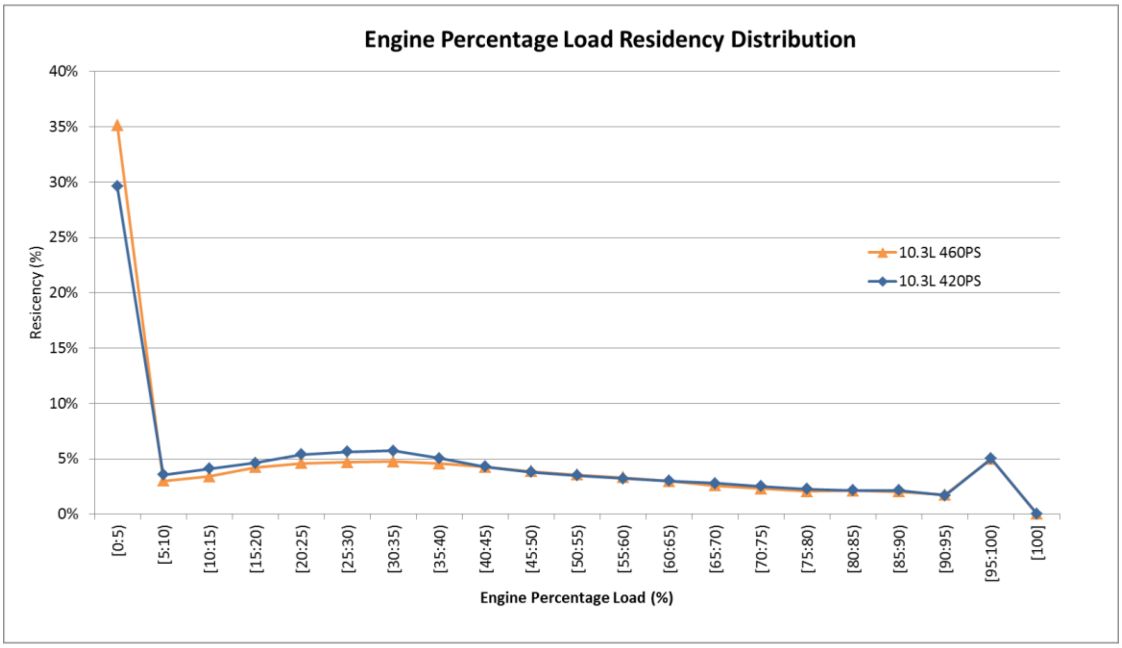


**Figure 4.6 :** Engine percentage load residency distribution.

### 4.1.3 Comparison of duty cycle with WHTC

Comparison of the developed cycle for trailer trucks at Turkey driving conditions is conducted with the Worldwide Reference Transient Engine Cycle (WHTC) that is developed for emission regulations. The objective of the WHTC is to create a worldwide harmonized engine test cycle for the heavy duty engines to conduct emission certification [2]. The WHTC cycle development study leaded by the UNECE Group of Experts on Pollution and Energy, research program was jointly conducted by TNO Automotive and TÜV Automotive. The cycle is targeted to be representative for world-wide usage of heavy duty engine operation. To conduct the correlation data from 9 light trucks, 20 rigid trucks, 18 trailer trucks and 11 public transport buses are collected at the locations from Europe, Australia, Japan and United States of America. In parallel vehicle usage statistics from field is collected. The field data from Turkey is not included in the study. WHTC cycle is not designed to represent the trailer truck usage profile specifically. Finally reference transient engine test cycle is developed. WHTC engine test cycle is subject to change with different engine applications.

In addition to homologation purposes for heavy duty engines, OEMs and component suppliers are using the WHTC cycle in the design of parts and design of tests. WHTC is also used as a comparison basis of engine performance and part durability among the heavy duty engine manufacturers. At the studies where the specific duty cycle is not available, it is common to use the most representative emission cycle. The purpose of comparing the WHTC cycle with the duty cycle developed in this study for Turkey trailer truck driving conditions is to understand how well the WHTC correlated with the Turkey trailer truck vehicle usage profile. To calculate the correlation value with respect to Turkey usage, the engine residency map for the emission cycle is created. Engine residency map consists of engine speed and engine percentage load. To create the WHTC cycle for 10.3L 420PS engine characteristic engine speed values, engine full load power curve, gear ratios and transmission ratios are entered to the WHTC drivetrain model and model is initiated to analyze the inputs. After entering the inputs, the WHTC time based cycle for 10.3L 420PS vehicle is obtained and converted into the residency map. The residency map can be found at the Figure 4.7. WHTC cycle results with different residency map regarding the inputs to the drivetrain model.

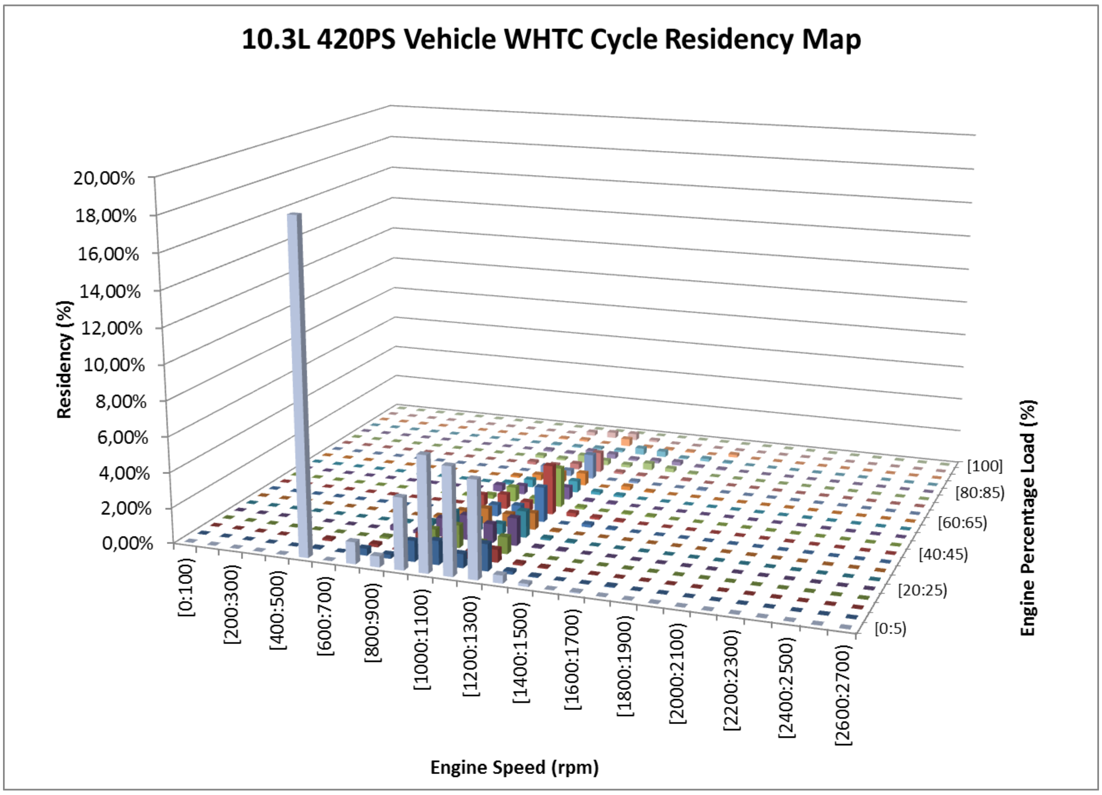


**Figure 4.7 :** 10.3L 420PS vehicle WHTC cycle residency map.

WHTC cycle is developed for heavy duty engines not limited with only trailer trucks. So that the cycle includes rigid truck, light truck and bus duty cycle too. At Figure 4.7 it is seen that there is high percentage of idle condition which is 18,45 % is present. At 420PS duty cycle calculated in this study the idle residency percentage to total time is 7,74 %. The possible cause of this difference may be that WHTC cycle covers public transportation buses and light trucks that are widely used in city conditions. So that in case of idle times, the WHTC is not correlated with the Turkey trailer truck duty cycle results in this study. Also it is observed that the high load residency at WHTC is lower compared to 420PS duty cycle study. If an engine component which has the high load points as most damaging is in interest, WHTC cycle will lead design and testing to under design which means the loss of the product quality.

At Figure 4.8 the engine speed residency distribution of the 420PS WHTC cycle and the 10.3L 420PS vehicle duty cycle can be found. It is observed that WHTC cycle has higher residencies at lower engine speeds while the duty cycle developed in this study for trailer truck applications has higher residencies at the engine speeds above 1300 rpm.

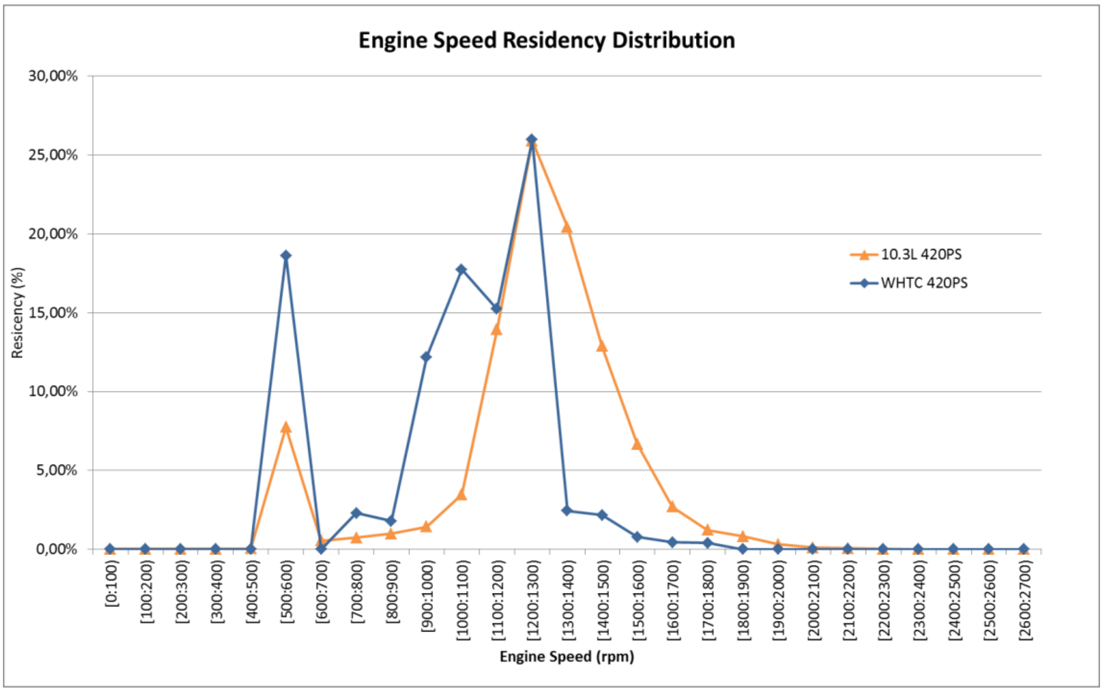


**Figure 4.8 :** Engine speed residency distribution including WHTC.

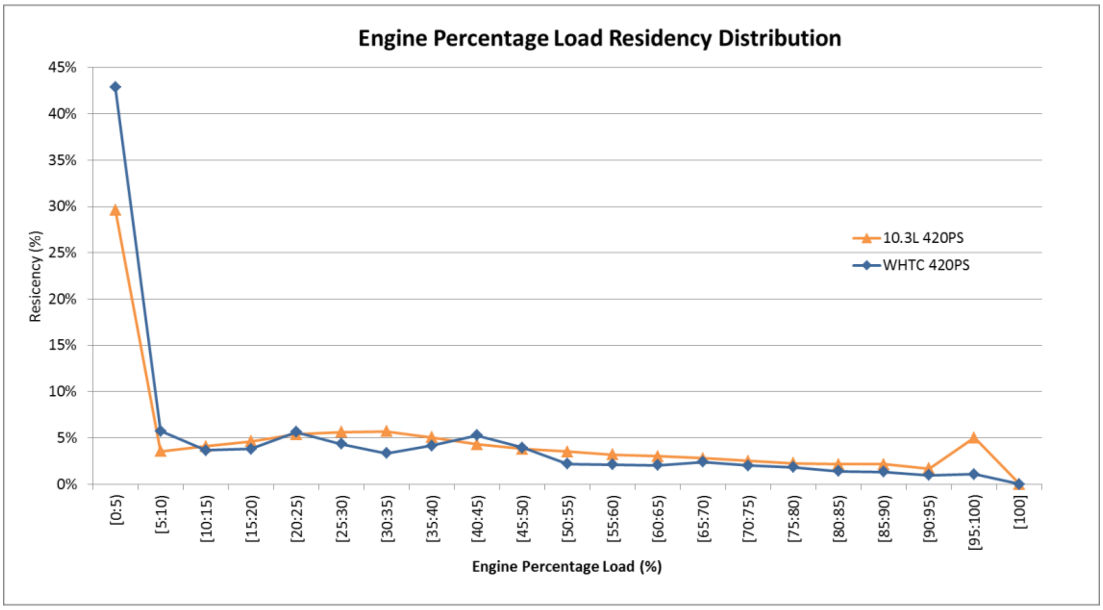


**Figure 4.9 :** Engine percentage load residency distribution including WHTC.

At Figure 4.9 the engine percentage load residency distribution of WHTC and the results from the developed duty cycle in this study are plotted. From the graph, it is seen that at low engine percentage load the residency of the WHTC cycle is higher while at higher loads the residency of the developed cycle is higher. The main differences are at 95 to 100 % region and 0 to 5 % region.

From the results, it is seen that the WHTC cycle does not have a good correlation with the developed duty cycle in this study. Apart from homologation purposes, such as engine design and test development, it can be more accurate and effective to develop duty cycles for the real world conditions rather than using WHTC directly.

### 4.2 General Operation Statistics of Drives

With a 10.3L 420PS vehicle and a 10.3L 460PS vehicle total 52550 km travelled. The detail of the each vehicle mileage can be found at Table 4.1.

**Table 4.1 :** Mileage of vehicles.

| | 10.3L 420 PS Vehicle | 10.3L 460 PS Vehicle |
|---|---|---|
| Distance Travelled (km) | 25450 | 27100 |

At Figure 4.10, average speed of each road type at two different vehicles can be found. The fastest road type is expressway for two vehicles and the slowest road type is rural. 10.3L 460PS vehicle shows a higher vehicle speed trend in all of three road types. None of the average speed value exceeds 63 km/h.

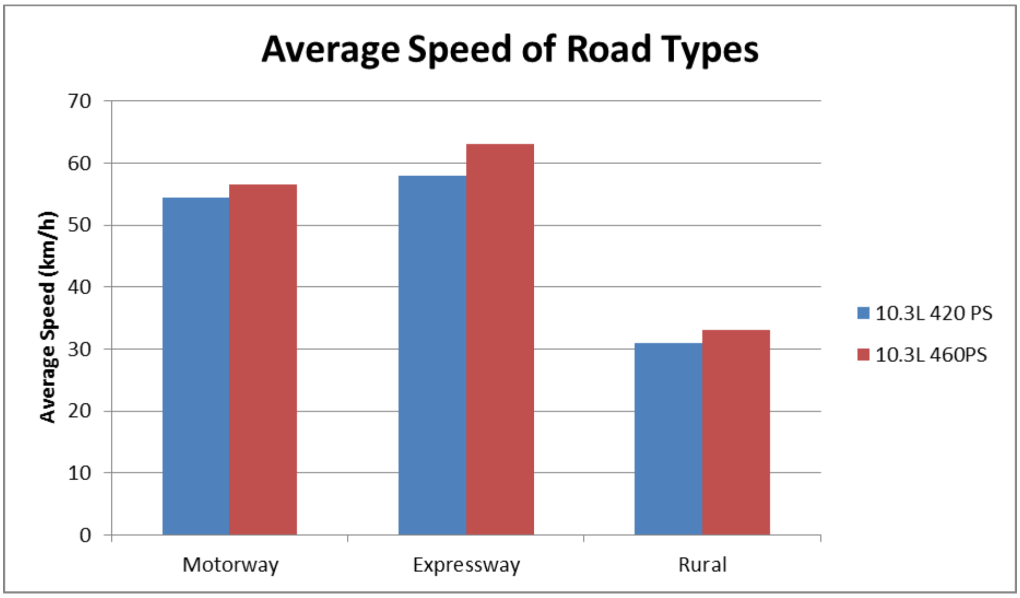


**Figure 4.10 :** Average speed of road types.

# 5. USE OF DUTY CYCLE

At prototype engine product development phase, engine duty cycle data plays a critical role. From design of engine components to validation, the durability calculation of the components which is intended to be correlated with the real world usage conditions requires an accurate field data study. Duty cycles support the optimization of the components by preventing the over and under design. Over design of the engine components is a high cost process and under design may lead earlier failures so that the optimal design solution should be found with the help of the correlated duty cycle data. The material of the components and the geometry can be optimized by conducting analytical life calculations using the duty cycle data. This process allows making design iterations and calculating the life of the component in a cyclic manner to find optimized solution. Understanding the field usage leads to design the parts that meet the end-user demand for a period of time.

In addition to design process, duty cycle data can be used to optimize engine dynamometer and component key life test development. To verify engine components against the specific failure modes, engine dynamometer and rig key life durability testing is one of the most efficient methods. Test cycles should reflect real world driver usage in terms of amplitude and frequency of stresses that the engine components will subject to at the field. Using the duty cycle and damage models, the acceleration of test load amplitude and time can be conducted in a correlated way. Acceleration could be made with various methods like removing non damaging points or increase stress level of cycle but all of the methods contain risks like creating failure modes which do not represent the ones experienced in real world driving conditions. Conducting acceleration on test cycle using damage mechanism requires a clear understanding of duty cycle in terms of stress and frequency. When any problems occur during the test, the maturity of the component with respect to field can be estimated if engine test is correlated with field usage by using the duty cycle data. In traditional test cycles, it is not possible to estimate the correlation of testing hours with the field so that only pass and fail information can be gathered.

Engine duty cycle data can be used for the calibration development purposes of engines. The high residency engine speed and engine percentage load areas can be found within the duty cycle and the calibration efforts of the engine can be focused on the those areas so that the end users can have an optimal strategy of the engine operation at the points where drivers use the vehicle more frequently.

# 6. CONCLUSIONS AND RECOMMENDATIONS

## 6.1 Conclusions

In this study, trailer truck engine duty cycle developed at Turkey driving conditions for 10.3L 420PS and 10.3L 460PS vehicle. To create duty cycle, discrete drive engine duty cycle methodology, which is based on to discretize real world driving behavior and road types, is used. Driver survey results are analyzed to define and weight the discrete drives. Data is collected from pre-defined discrete drives with professional drivers using two different vehicles. Drives are combined with the classification matrix weights to develop duty cycle for 10.3L 420PS and 10.3L 460PS engines.

It is observed that the engine speed residency at 1000 rpm to 1800 rpm is much higher compared with other regions on both engines. The main difference between the engines in terms of engine speed is that 10.3L 420PS engine speed residency is much higher at the region from 1100 rpm to 1400 rpm. At other regions on the engine speed residency distribution, except idle speed, 10.3L 460PS engine has higher residency.

From the duty cycle results, it is seen that the no load and low engine percentage load region has at least 30 % residency of the total drive. This result is validated with the WTHC model which predicts 44 % residency of the total drive at no load and low engine percentage load regions. The engine percentage load residency at no load and low load regions is 5 % higher at 10.3L 460PS engine and at other regions the residency of the 460PS engine is slightly lower than 420PS but following the same trend. It is seen that there is a peak at the 95 % to 100 % load region on both engines which is not observed at WHTC results.

There is a large difference in terms of engine speed and engine load residency between WHTC and the duty cycles in this study. The emission cycles are not effective for engine development and engine test cycle development processes because the emission cycles are not designed for specific power and vehicle applications.

## 6.2 Recommendations and Future Work

Future work can include the correlation of developed engine duty cycle with the real world usage conditions, collecting data from real world drivers with the vehicles at serial production. This method will help engineers to understand the accuracy of the discrete drive methodology for trailer truck usage in Turkey for both power variants.

In future applications, GPRS data loggers can be used to shorten the data analysis and data collecting time. It will also decrease the complexity of the project and will enable to give fast reactions to issues at the field. With fast data retrieval, the active planning can be achieved. With active planning, data from the field can be analyzed instantly and if the two different drives on same driving behavior and route type are statistically close, the other planned recurrent drive can be removed from the plan. It will help to reduce the total time and the total cost of the future projects.

The engine duty cycle library can be created using different power to weight ratio engine variants for the projects in the future. This process will enable to conduct design modifications and test cycle development studies at very first phases of the engine development studies. This process can be effective to make first phase design calculations until the first duty cycle study is completed.

Using the collected engine duty cycle from different engine variants, a model can be developed which is based on the correlation of the duty cycle data with the engine parameters. With this model, engineers can predict the duty cycle of the engine at the design phase of the engine. The built in models can be correlated with the field data to increase the accuracy when engine is passed to serial production.

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